United States Nuclear Regulatory Commission

UPDATE ON ISSUES IN 1998 AGENCY PROGRAM PLAN FOR HIGH-BURNUP FUEL

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Office of Nuclear Regulatory Research

ACRS Subcommittee

October 9, 2002

ORIGINAL LIST OF ISSUES

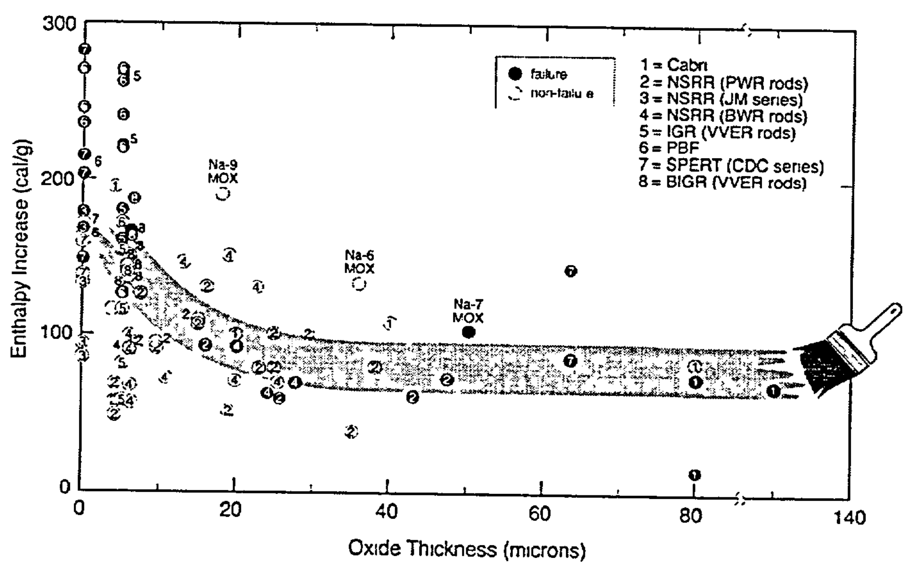
1	Cladding Integrity and Fuel Design Limits	Resolved in original plan (no further discussion)
2	Control Rod Insertion Problems	Resolved in original plan (no further discussion)
3	Criteria and Analysis for Reactivity Accidents	NRC confirmatory assessment at 62 GWd/t, early 2005. Revision of Reg Guide 1.77, TBD.
4	Criteria and Analysis for Loss-of-Coolant Accidents	Zircaloy criteria and models at 62 GWd/t, 2004. New performance-based criteria possible.
5	Criteria and Analysis for BWR Power Oscillations (ATWS)	Schedule to be determined
6	Fuel Rod and Neutronic Computer Codes for Analysis	Resolved
7	Source Term and Core Melt Progression	Technical issues essentially resolved. Revision of Reg. Guide 1.183, TBD.
8	Transportation and Dry Storage	Research Information Letter, 2004
9	High Enrichments (>5%)	No activity needed now (no further discussion)

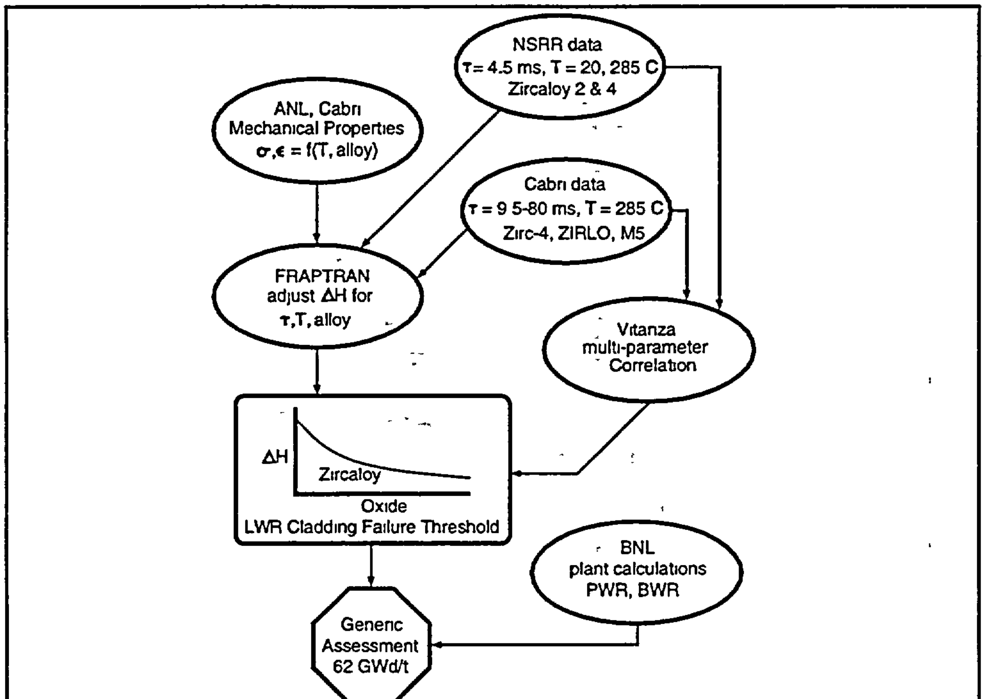
CRITERIA AND ANALYSIS FOR REACTIVITY ACCIDENTS

ISSUE: 280 cal/g regulatory limit in Reg. Guide 1.77 is not adequate for high-burnup fuel. New limit needed.

METHOD: (see following slides)

SCHEDULE:
Cabri test(s) late 2002 (early 2003)
ANL Zircaloy mechanical properties 2003
NSRR Zirc. tests in high-temp. capsule late 2004
NRC confirmatory assessment 62 GWd/t early 2005



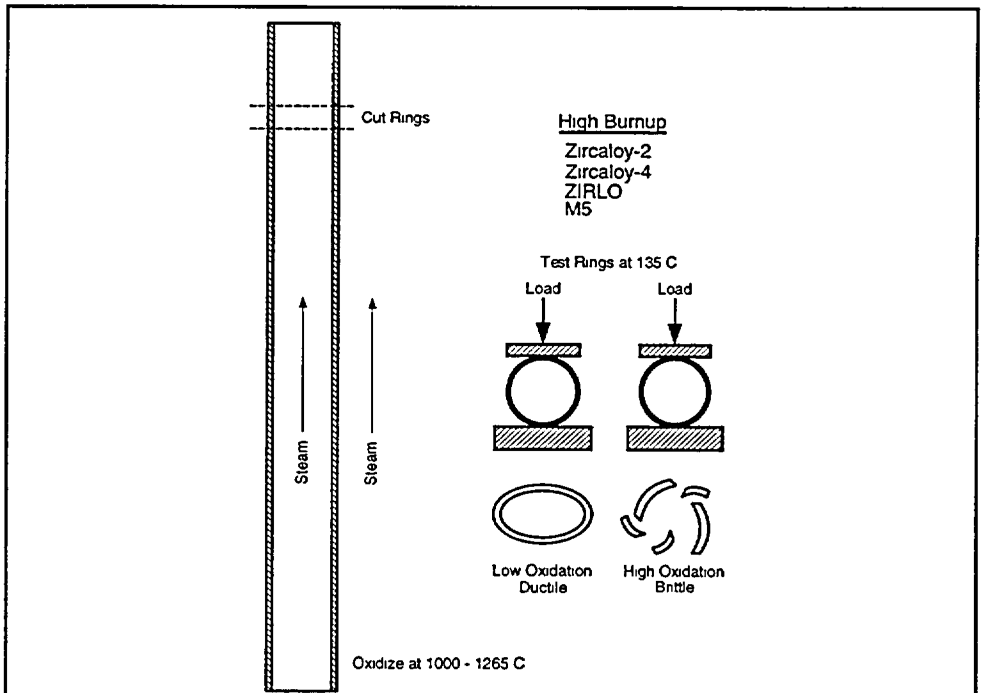


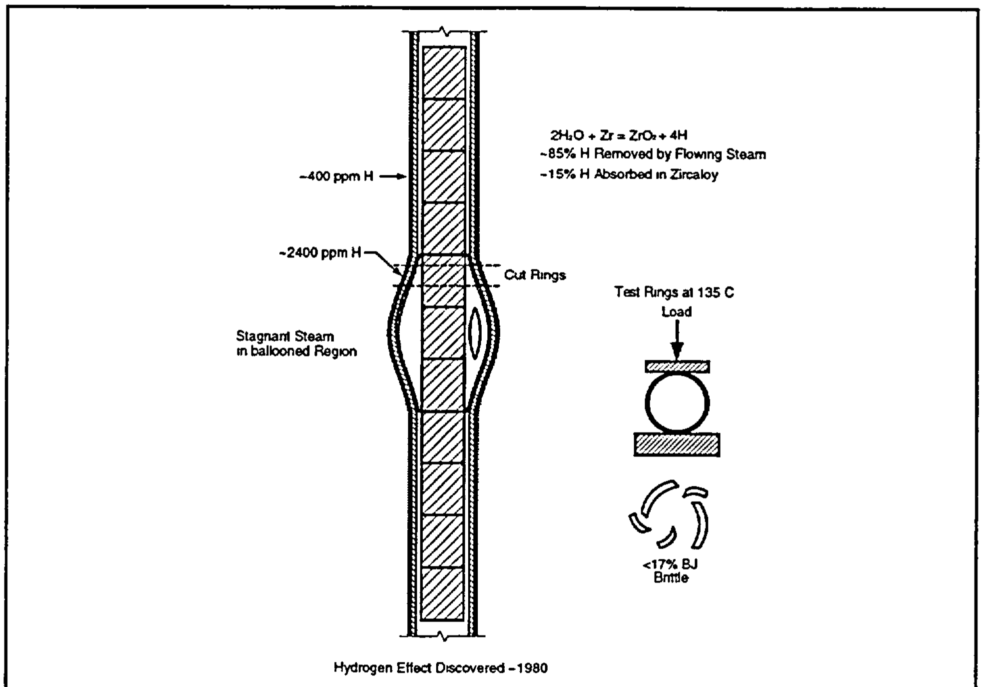
CRITERIA AND ANALYSIS FOR LOSS-OF-COOLANT ACCIDENTS

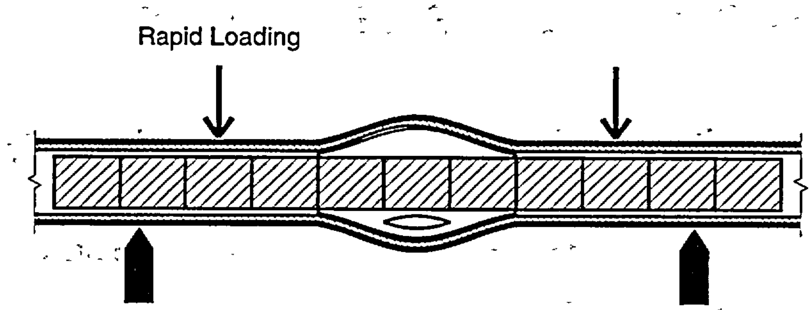
ISSUE: Embrittlement criteria in 10 CFR 50.46 and related evaluation models are probably affected by burnup and alloy. Check and revise if necessary.

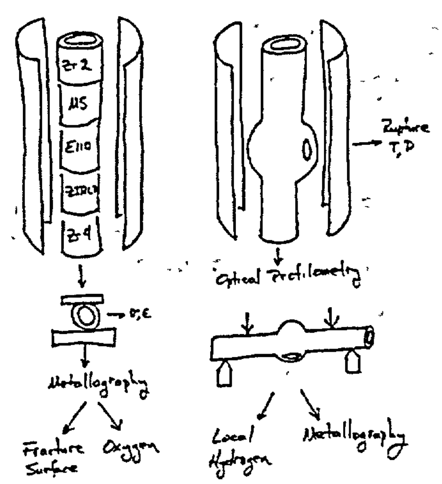
METHOD: (see following slides)

SCHEDULE: Zircaloy criteria and models at 62 GWd/t in 2004


Cut Rings
High Burnup
Zircaloy-2
Zircaloy-4
ZIRLO
M5
Test Rings at 135 C
Load
Load
Steam
Steam
Low Oxidation
Ductile
High Oxidation
Brittle
Oxidize at 1000 - 1265 C


$2H_2O + Zr = ZrO_2 + 4H$
~85% H Removed by Flowing Steam
~15% H Absorbed in Zircaloy
~400 ppm H
~2400 ppm H
Cut Rings
Test Rings at 135 C
Load
Stagnant Steam
in ballooned Region
<17% BJ
Brittle
Hydrogen Effect Discovered ~1980


Rapid Loading


Zr2
M5
E110
ZIRLO
Zr4
Rupture
T, P
Optical Profilometry
σ, ε
Metallography
Fracture Surface
Oxygen
Local Hydrogen
Metallography

CRITERIA AND ANALYSIS FOR BWR POWER OSCILLATIONS (ATWS)

ISSUE: 280 cal/g limit currently used may not be adequate to ensure benign result in PRA for "successfully" terminated oscillations

METHOD: Analytical + some experimental separate effects

SCHEDULE: TBD

FUEL ROD AND NEUTRONIC COMPUTER CODES FOR ANALYSIS

ISSUE: NRC codes did not have high-burnup capability and were needed to help review vendor codes for high-burnup applications.

METHOD: Develop, assess, peer review

SCHEDULE: Resolved

SOURCE TERM AND CORE MELT PROGRESSION

ISSUE:	Applicability of NUREG-1465 source terms to high-burnup fuel
METHOD:	Expert elicitation, more data
SCHEDULE:	Expert elicitation completed in June 2002 VERCORS, PHEBUS, VEGA data as available Revision of Reg. Guide 1.183 TBD

TRANSPORTATION AND DRY STORAGE

ISSUE:	What is the effect of burnup on fission product inventory (shielding, heat source, activity) and cladding degradation (removal from storage)?
METHOD:	Direct tests and measurements
SCHEDULE:	ANL tests on Zircaloy in 2003 Research Information Letter in 2004

EPRI Topical Report on Reactivity Initiated Accidents

Undine Shoop
Office of Nuclear Reactor Regulation
October 9, 2002

RIA Criteria History

- RG 1.77 – May 1974
  - Original Criteria of 280 cal/gm
- NRR User Need Request – October 4, 1993
  - Evaluate Fuel Failure Thresholds for Normal Operation and RIA
- Commission Memorandum – July 15, 1997
  - Adequacy Assessment of Regulatory Guidelines and Licensing Criteria for High Burnup Fuel

RIA Criteria History - Continued

- Research Information Letter No. 174 – March 3, 1997
  - Proposed Changes to the RIA Criteria
- Agency Program Plan for High Burnup Fuel – July 6, 1998
  - Industry will have to provide the Criteria, Data base, and Models for Burnup > 62 GWD/MTU
  - Industry will have to perform the research necessary to develop the data base to support extended burnup ranges > 62 GWD/MTU
  - RES will confirm criteria for burnup < 62 GWD/MTU

Industry Response

- EPRI Robust Fuels Program
  - Included an objective of developing industry wide criteria, data, analysis and methodology to achieve industry burnup extension > 62 GWD/MTU
  - EPRI RIA topical report is the first industry submittal to develop the criteria to support industry high burnup extension

EPRI Criteria

- Two criteria approach proposed consistent with current RG 1.77 criteria
  - Criteria for long term cooling following an accident
  - Criteria for radiological release following a cladding failure

EPRI Topical Report on Reactivity Initiated Accidents – Part 2

Undine Shoop
Office of Nuclear Reactor Regulation
October 9, 2002

NRC Preliminary Review Plan Purpose

- To focus resources appropriately to provide a detailed review and identify all the elements needed to complete the review

NRC Preliminary Review Plan Elements

- Data Verification
  - Correct application in the methodology
  - Correct application in a manner consistent with the methods used to generate it
  - Statistically sound combination of the data sets
- SED/CSED Theory and Model
  - Investigation and verification of the equivalence of SED/CSED model to Rice's J/Jc formulation
  - FRAPTRAN independent verification
- Fuel Rod Failure Threshold
  - Validation of this application
  - Review of applicability to current and future proposed fuel types
- Core Coolability Limit
  - Application verification

NRC Preliminary Review Plan Elements – Cont.

- FALCON Code
  - Review of the code
- Fuel Dispersal
  - Review data for applicability of the phenomena to the proposed safety limit
- Uncertainty and Conservatism
  - Data uncertainty verification
  - Conservatism confirmation
- Limitations of the Criteria
  - Review data for limits of applicability which would create limitations of the methodology application
- Safety Evaluation Conditions of Acceptance
- Revision of associated RG and SRPs

Preliminary RES Assistance Needed

- Data Verification
- SED/CSED Theory and Model
- Fuel Dispersal

Future Activities

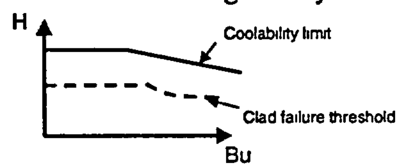
- Final Review Plan – December 31, 2002

EPRI

Outline

- Industry effort for preparing the RIA (Reactivity Initiated Accident) Topical- Yang
  - Experimental and analytical effort
  - RepNa-1 is an outlier
  - CABRI Water Loop Project

- Bases for RIA Fuel Failure and Core Coolability Acceptance Criteria - Montgomery



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Lower RIA Limits For High Burnup Fuel ?

- CABRI RepNa-1 test (November, 1993) raised concerns about RIA fuel failure limits and fuel dispersal for high burnup fuel

  Materials
  - High burnup (64 GWD/T) Zr-4 cladding
  - Oxide=80 μm with extensive spallation

  Test Conditions
  - Narrow (9.5 ms) pulse width
  - Low pressure Na-loop

  Test results
  - Reported failure enthalpy ~30 cal/g- low failure level
  - Fuel dispersal observed

EPRI

Significant Progress Made Since 1994

- Many RIA-simulation tests performed since 1994
  - 11 CABRI tests from France
  - 36 tests NSRR tests from Japan
  - **RepNa-1 results never duplicated**
- Considerably more knowledge and data now available
  - Good understanding and agreement from conferences and published papers on the RIA failure mechanisms
    - Data are consistent if differences in key experimental parameters are accounted for
      - Cladding ductility, temperature, pulse width
  - Analytic tools capable of predicting RIA response are available
    - FALCON, SCANAIR, and FRAPTRAN
    - Model calculations are consistent with experimental results, except RepNa-1

EPRI

Significant Progress Made Since 1994 (cont'd)

- First industry evaluation of RIA *(EPRI report, 1996)*
  - Recognized core coolability limit of 230 Cal/g
  - Proposed burnup-dependent failure limit based on "Region of Success"
    - Based entirely on RIA simulation tests
  - Many countries have used the "Region of Success"
    - A Very conservative approach
- As the knowledge base increases, new, more realistic approach is appropriate. The industry has:
  - Used FALCON, mechanical property data and RIA simulation tests to develop a revised **failure limit**
  - Adopted "no incipient melting" to ensure **coolability**
- New failure limit is consistent with experimental data and is similar to "region of success"
  - Supported by mechanical property data and RIA-simulation tests

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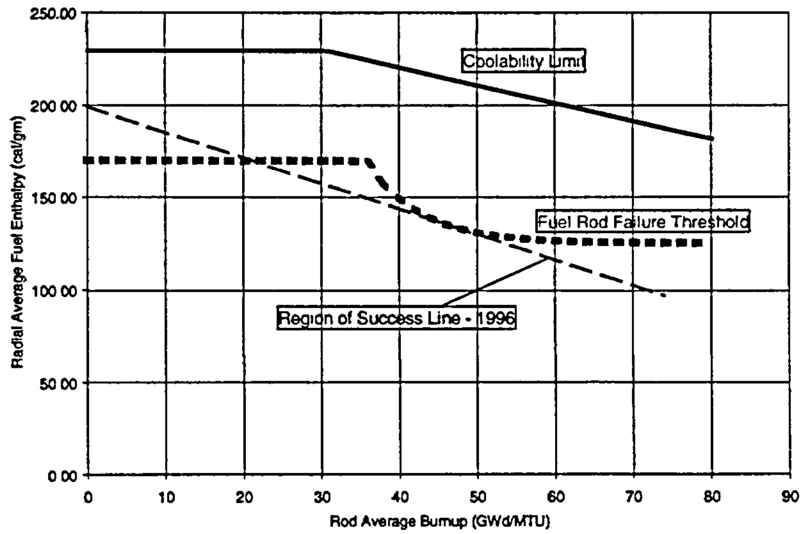
RIA Criteria



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RepNa-1 Task Force Formed

- RepNa-1 is an outlier
  - Much lower failure enthalpy compared to other RepNa tests
  - Failure did not initiate at peak power location
  - None of the codes can explain the test results
- Concerns raised:
  - Pre-existing defects
  - Accuracy of the timing of failures (interpretation of signals)
    - Narrow pulse
    - Failure occurred during the steep rise of the pulse
  - Unique pre-conditioning conditions
  - Microstructure
- RepNa-1 Task Force formed within the CABRI International Project in October, 2000
  - To perform an objective investigation of RepNa-1

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Technical Reasons To Revisit Rep Na - 1

	Burnup (Gwd/t)	Oxide (micron)	Pulse width (ms)	H at failure (cal/g)	Comment
Rep Na -1	65	80-100 (spalled)	9.5	30	Fuel dispersal
Rep Na –5	64	20	9.1	No Failure (Peak H=113)	1% strain
Rep Na –8	60	130 (spalled)	75	82	No fuel dispersal
Rep Na – 10 (Sibling of RepNa-1)	64	80 (spalled)	31	79	No fuel dispersal

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Two Major Areas Investigated By The RepNa-1 Task Force

- Uncertainties in signal analysis: microphones, different recording systems: flow meters and pressure sensors, have been used to record the timing (and enthalpy level) for rod failures & fuel dispersal
  - The reported low value was based on microphone signals
    - The acoustic signals could come from events other than failures, as demonstrated in RepNa-8
  - Significant uncertainties exist for pressure sensors and flow meters
    - Conflicting failure time from different recording systems
    - Very small volume displacement involved
  - Difficult to retrieve detailed data (generated long time ago)

Current conclusion based on signal analysis: the failure occurred between 30-50 cal/g (NOT the 30 cal/g reported)

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Two Major Areas Investigated By The RepNa-1 Task Force (Cont'd)

- Microstructures investigations
  - Artifact found after the re-fabrication
  - Pre-conditioning of RepNa-1 may have embrittled the cladding (Hee Chung hypothesis-LWR Fuel performance, April, 2000, Park City, Utah)
    - 380C for 14 hours (RepNa-1) vs. 310C for 12 hours
  - Cladding ductility and failure modes of RepNa-1, 8 and 10
- Current status
  - Work in progress, final report expected in 2003
  - Failure initiation site (90 ± 20 mm) identified by IRSN is partly ductile, peak power node (280 mm) is entirely brittle
    - PIE indicated multiple cracks with fuel loss
    - The "artifact" could not be found after the test
    - Failure could have been initiated at other locations
  - Currently reviewing mechanical property tests (PROMETRA) data and fractography for relevance to RepNa tests

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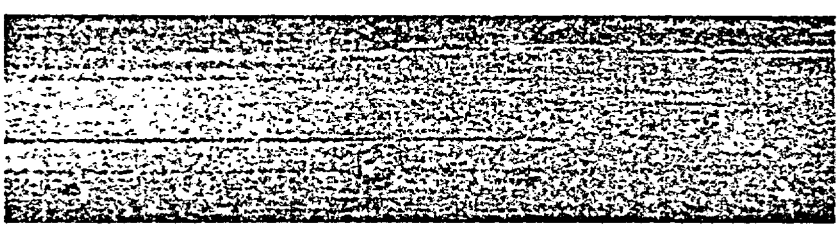
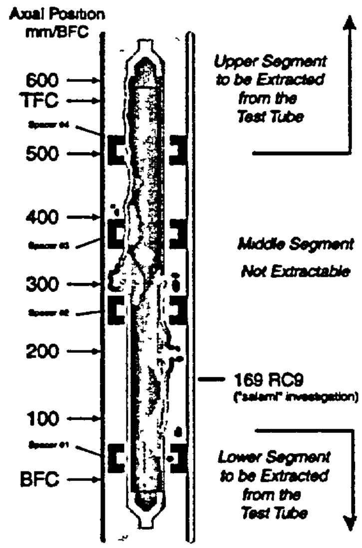
Artifact Observed After Re-Fabrication

(prior to test)



Schematic Of RepNa-1 After The Test



RepNa-1 Not Included In Deriving The Criteria

- Concerns investigated by RepNa-1 Task Force are significant:
  - Inconsistent timing of failure from different recording systems
  - Relevance of preconditioning temperatures
  - Artifact introduced during re-fabrication
  - Microstructures
- Sufficient number of more representative RIA-simulation tests form a consistent data base
  - RepNa-1 has significant spallations
    - Modern PWR claddings have better corrosion performance
      - M5, Zirlo and low-tin Zr-4
  - RepNa-1 has very narrow pulse (9.5 ms)
    - Typical PWR pulse is around 30 ms

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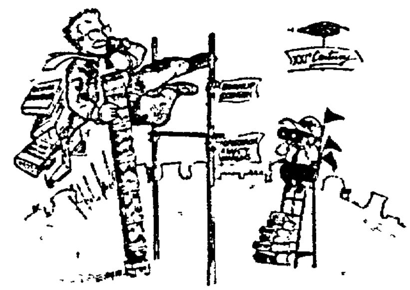
RIA Evaluation Is A Key Component Of The Robust Fuel Program (RFP)

- RFP Vision: High performance fuel for a competitive world.
- Utilities take charge to ensure
  - No operational surprises (fuel performs as advertised)
  - No regulatory surprises
  - Burnup extension



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Effort For Burnup Extension

- For burnup extension, NRC has mandated
  - The industry to propose a consistent set of criteria
  - Provide the data necessary to develop the criteria and to demonstrate compliance
- Three major RFP focus for burnup extension
  - Industry Guide
    - Framework for burnup extension
  - RIA
  - LOCA
- Robust Fuel Program has conducted/planned programs to confirm margins of current high-duty fuel designs and establish the bases for burnup extension
  - Poolside and hotcell exams, lab tests

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Recent Industry Effort

- Conducted poolside and hot cell campaigns
  - **BWR**
    - Limerick rods at 57 GWD/T
    - Limerick rods at 70 GWD/T with and without NMCA (Noble Metal Chemical Addition)
  - **PWR**
    - North Anna Zirlo at 70 GWD/T
    - North Anna M5 at 70+ GWD/T (2004)
  - Will obtain high burnup data under high-duty conditions
    - Fission gas release, corrosion, hydriding, mechanical property and others
  - Rods have also been used for safety research
    - LOCA and RIA

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Recent Industry Effort (Cont'd) – RIA

- Developed RIA Topical
- Actively participating in CABRI International Water Loop Project
  - Additional 12 tests in prototypical PWR loop planned
  - Will provide
    - RIA-simulation tests of fuel rods with advanced alloys (in 2002)
    - Tests with higher burnup fuel (>70-80 GWD/T)
    - Data on fuel/coolant interaction above the proposed failure limit
    - Mechanistic understanding on the effects of pulse width, microstructure, etc.

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Cabri's international project

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Proposed Test Matrix/Schedule Cabri Project

- CIP-0 series: Two tests in the Na-loop in 2002
- CIP-Q :Qualification test for the water loop in 2005
- CIP-1 : Tests in water loop, comparison tests of CIP-0 tests, 2006+
- CIP-2: High burnup UO2 fuel, >80 GWD/T
- CIP-3: Mechanistic understanding on effects of pulse width, fuel microstructure, etc
- CIP-4 Study of high burnup MOX fuel, > 60 GWD/T
- CIP-5 To be defined

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CIP0 Tests Will Determine Future Scope Of RIA

- RIA criteria proposed was based on Zircaloy clad
- Two additional RIA tests in CABRI Na-loop in 2002
  - CIP0-2
    - M5 rod (~ 20µm, ~73 GWd/T)
    - Test will be performed in 10/02
    - 30 ms, with enthalpy of ~95 cal/g (based on calculations)
  - CIP0-1
    - ZIRLO rod (~ 100µm, ~73 GWd/T)
    - Test will be performed in 11/02
    - 30 ms, with enthalpy of ~90 cal/g (based on calculations)
- New parameters involved
  - Higher burnup, 63 GWD/T → 73 GWD/T
  - New alloys, M5 and Zirlo

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Industry Has Submitted The RIA Topical

- Based on extensive data coupled with analytical evaluations
  - Over 80 RIA-simulation tests using irradiated rods
  - Extensive corrosion and mechanical property tests
  - Analysis and experiments on fuel/coolant interaction
- RIA tests to be performed in 2002 using high burnup LWR rods with advanced alloys
  - Confirm the conservatism in proposed criteria
  - Can be used to develop criteria for advanced alloys
- Data from the Cabri Water Loop Project will NOT change conclusions of the current RIA Topical
  - Na-loop test results are conservative (lower clad temperature)
  - DNB-induced failure mechanisms are NOT expected at the proposed failure limits
  - Will provide margins and enhanced understanding of post-CHF rod behavior

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Bases for RIA Fuel Failure and Core Coolability Acceptance Criteria

Robert Montgomery
Nicolas Waeckel
Rosa Yang

ACRS Reactor Fuels Subcommittee Meeting
NRC Offices
Washington, D.C.
October 9, 2002

Robust Fuel Program

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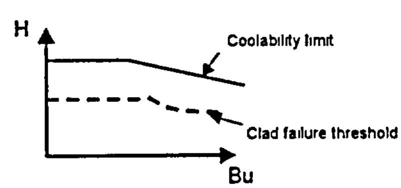
Presentation Outline

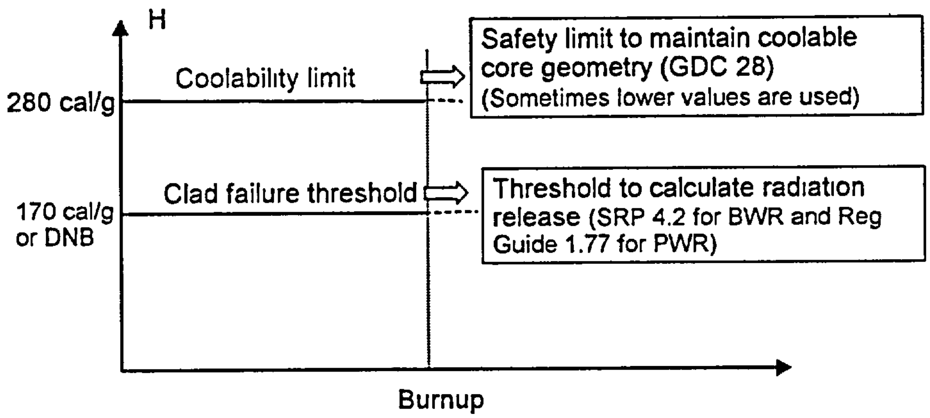
- Regulatory basis
- Database of RIA-simulation tests
  - integral test characteristics and test conditions
- Fuel Rod Failure
  - Clad failure mechanisms at low and high burnup
  - Clad failure model for PCMI
  - Revised fuel rod failure threshold
- Core Coolability
  - Core coolability issues
  - Revised core coolability limit
- Summary



Robust Fuel Program

Regulatory background

- Separate clad failure threshold and coolability safety limit



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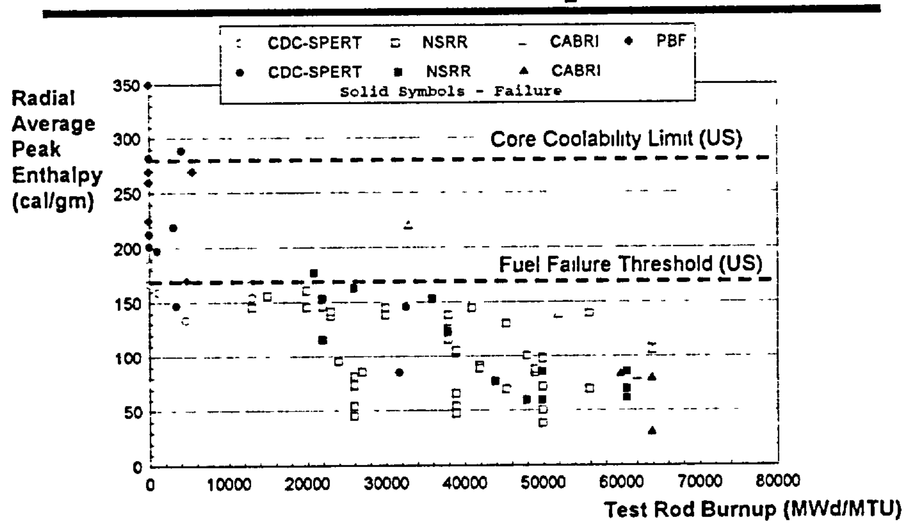
Database of RIA-Simulation Tests on Irradiated UO_2 Fuel



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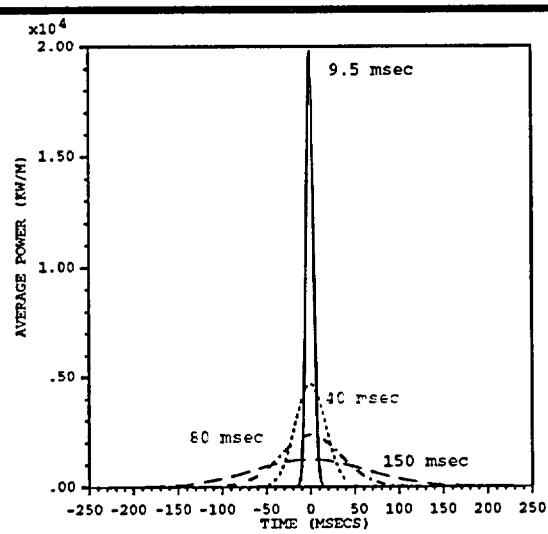
Comparison of RIA Power Pulse Shapes



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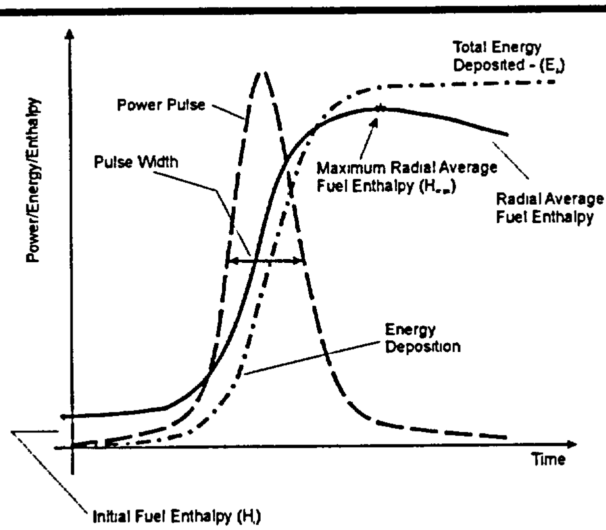
RIA Power Pulse Characteristics



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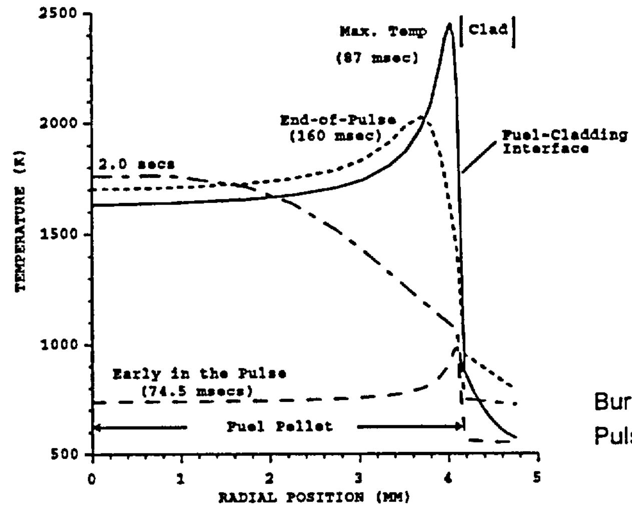
Fuel Rod Temperature Profiles



Burnup = 65 GWd/tU
Pulse Width 9 5 ms

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Test Conditions vs. LWR

	SPERT-CDC	NSRR	CABRI	LWR
Number of Tests	> 15	> 50	12	
Coolant Conditions				
Type	Stagnant Water	Stagnant Water	Flowing Sodium	Flowing Water
Temp (°C)	25	25	280	280 - BWR 290 - PWR
Pressure (atm)	1	1	3	70 - BWR 150 - PWR
Pulse Characteristics				
Full-Width Half Max. (msec)	13 to 31	4.5 to 6.6	10 natural 30-80 pseudo	25 to 90
Deposited Energies (cal/gm)	160 to 350	20 to 200	100 to 200	TBD

⇨ Need analytical tools to assess tests results and compare to LWR conditions

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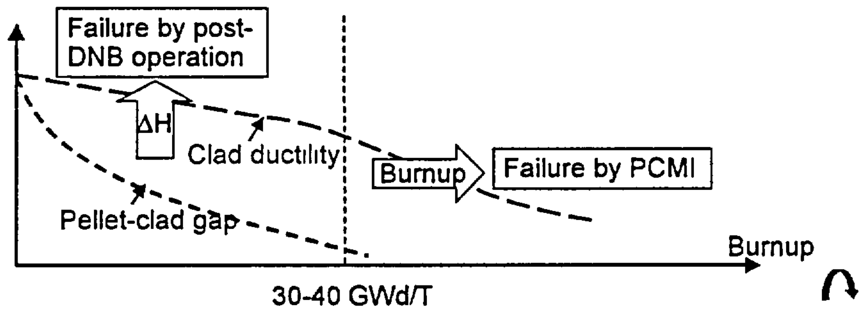
Clad failure mechanisms

- Based on over 100 RIA-simulation tests, the clad failure mechanisms are:
  - Low Burnup high temperature failure caused by post-DNB operation (clad oxidation / embrittlement or clad ballooning)
  - High Burnup Pellet Clad Mechanical Interaction (PCMI) combined with loss of clad ductility



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Clad failure mechanisms at high burnup

- Clad failure mechanism is PCMI resulting from fuel thermal expansion and fuel matrix fission gas swelling
  - ⇨ Cladding **ductility** is the key determining factor
  - ⇨ Conclusion of the PWR RIA PIRT Report (NUREG/CR-6742)
- Fuel rod failure depends mainly on cladding ductility NOT on burnup
  - Corrosion/hydriding and fuel duty define clad residual ductility
  - Spalled rods have significantly less ductility than non-spalled rods
    - » CABRI database shows NO failure up to 64 GWd/TU for non-spalled rods

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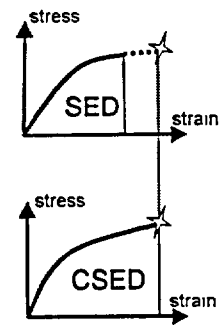
Clad Failure Model for PCMI Conditions

- Strain Energy Density (SED) is a measure of loading intensity on the cladding
  - SED is a calculated response parameter, based on integrating stress and strain
  - Addresses the effects of strain rate, temperature and stress biaxiality
- Critical SED is a measure of cladding failure potential or cladding residual ductility
  - CSED is determined from mechanical property tests
  - depends mainly on H level, temperature and materials
- Cladding failure occurs when SED reaches the CSED for a given clad material



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Extensive Database of Cladding Mechanical Properties

Program	Fuel Type	Max Bu (GWd/tU)	Max Fast Fluence (n/cm^2)	Range of Oxide Thickness (μm)	Temperature Range (K)	Strain Rate (/sec)
ESEERCO Hot Cell Program on Zion Rods						
Burst	15x15	49	9.4×10^{21}	15 - 25	588	2×10^{-5}
ABBCE-DOE Hot Cell Program on Fort Calhoun Rods						
Burst	14x14	53	8×10^{21}	30 - 50	588	6.7×10^{-5}
EPRI-B&W Hot Cell Program on Oconee-1 Rods						
Axial Tension Ring Tension Burst	15x15	25	5×10^{21}	< 20	616	8×10^{-5}
EPRI-ABBCE Hot Cell Program on Calvert Cliffs-1 Rods						
Axial Tension	14x14	68	12×10^{21}	24 - 110‡	313 - 673	4×10^{-3}
Ring Tension				24 - 115‡	573	4×10^{-3}
Burst				36 - 110‡	588	6.7×10^{-3}
ABBCE-DOE Hot Cell Program on ANO-2 Rods						
Axial Tension	16x16	58	12×10^{21}	24 - 46	313 - 673	4×10^{-3}
Burst				24 - 46	588	7×10^{-3}
EdF-IPSN PROMETRA Program						
Ring Tension	17x17	63	10×10^{21}	20 - 120‡	298 - 673	01 - 5
Nuclear Fuel Industry Research Program-III						
Burst	15x15	51	9×10^{21}	40 - 110‡	573 - 623	5×10^{-5}

‡ - Several samples were obtained from cladding with spalled oxide layers

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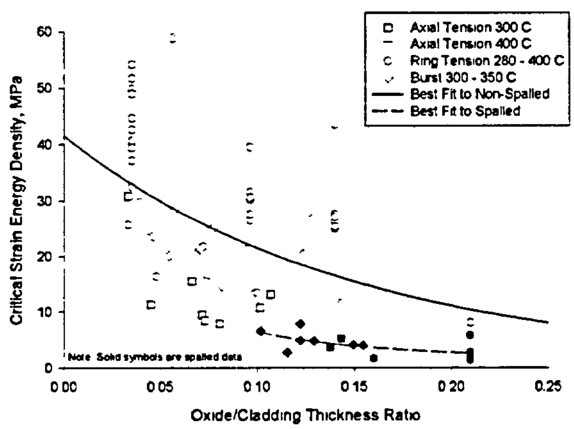
Cladding CSED Database



- Scatter is more related to test conditions and specimen design artifacts rather than to material variability
- Improved test designs will reduce the scatter
- Use of best-fit curves is justified when compared with failed-unfailed RIA database

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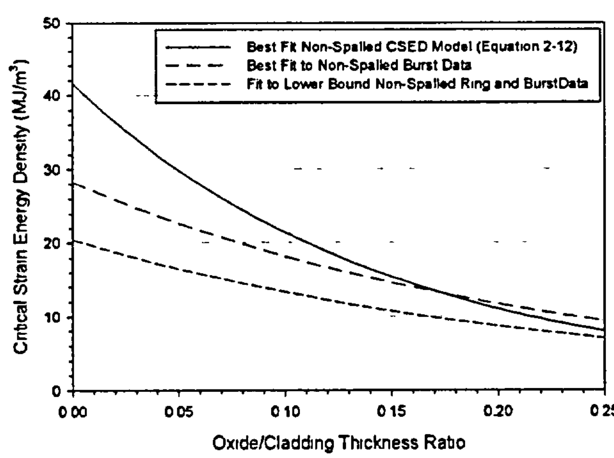
Different Data Evaluation Methods



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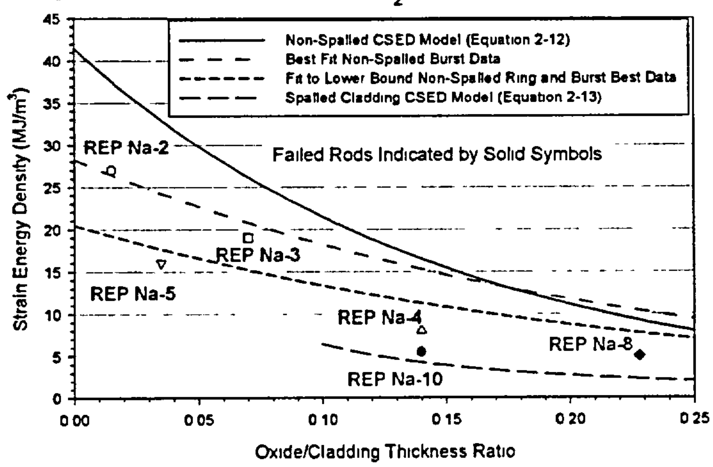
Robust Fuel Program

EPRI

Analysis of High Burnup RIA-Simulation Tests

CABRI REP Na Tests on UO_2 Rods in Sodium Coolant



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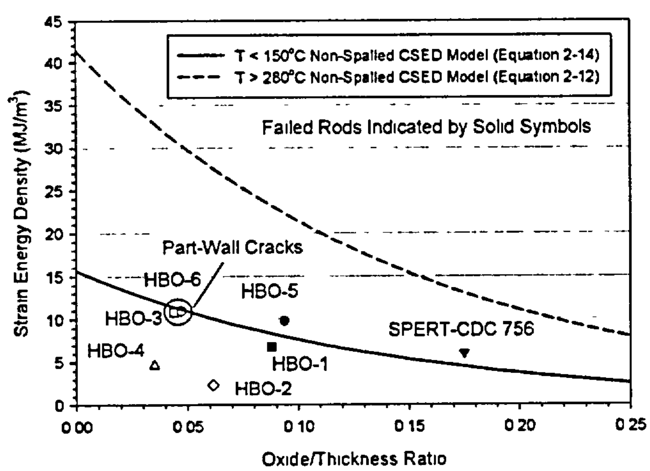
Robust Fuel Program

EPRI

Analysis of High Burnup RIA-Simulation Tests

NSRR Tests on UO_2 Rods in Ambient Water



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Robust Fuel Program

EPRI

Development of Fuel Rod Failure Threshold

- Construct Fuel Rod Failure Threshold Consistent with Current Licensing Approach
  - Radial Average Fuel Enthalpy at Failure as a Function of Rod Average Burnup
  - Conservative Zircaloy-4 "Corrosion vs Burnup" Correlation Used
    - » Relationship between cladding oxidation and rod average burnup

Robust Fuel Program

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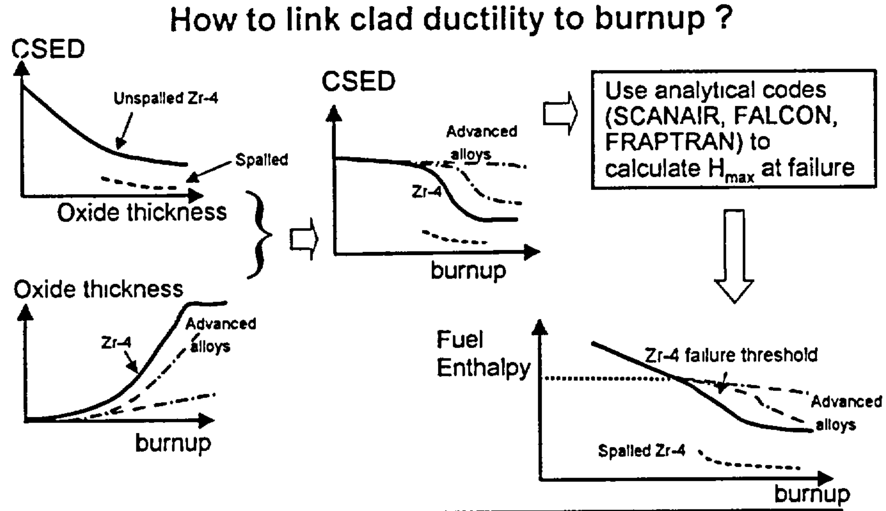
Approach to Develop Fuel Rod Failure Threshold

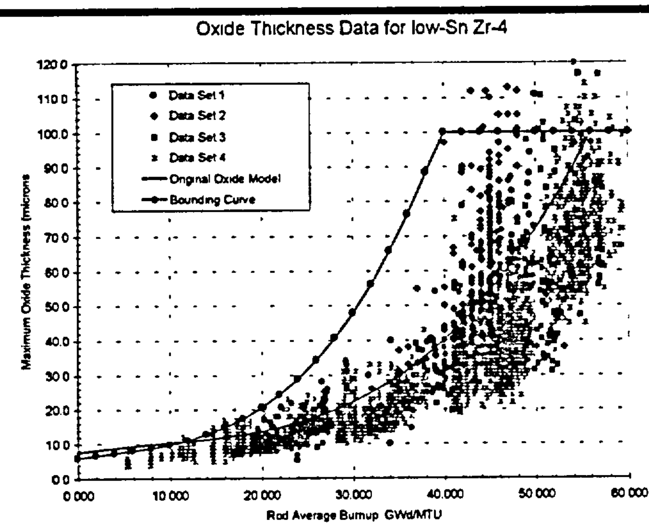
How to link clad ductility to burnup ?



Robust Fuel Program

EPRI

Maximum Oxide Thickness versus Burnup



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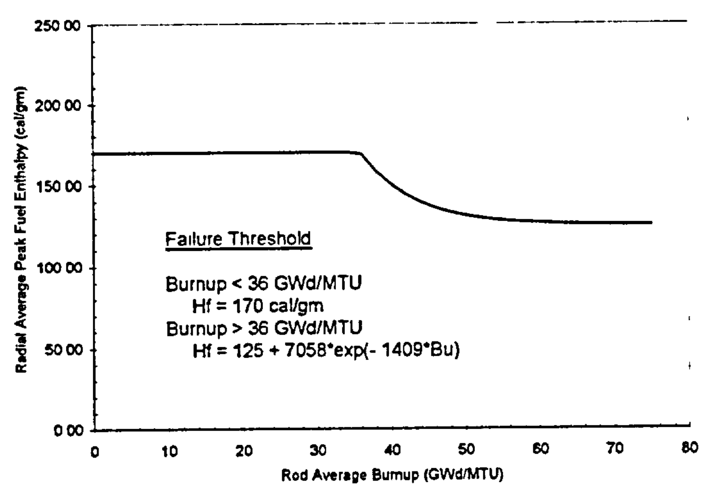
Revised Fuel Rod Failure Threshold



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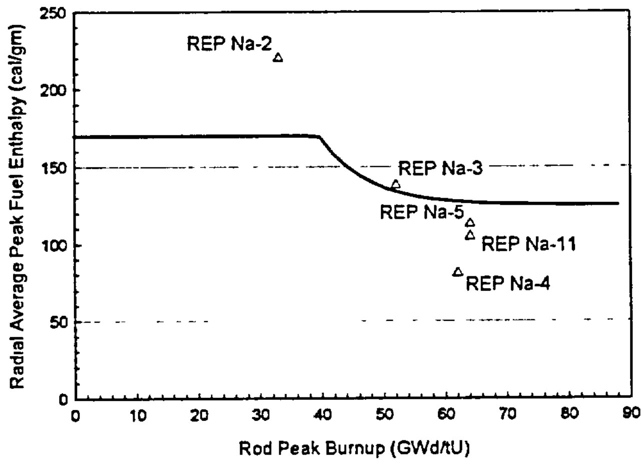
Failure Threshold Bounds CABRI Test Data With Non-Spalled Oxide Layers

(CABRI Tests in Sodium Coolant - 280°C)



Note Test Data Represent Rod Peak Burnup

Robust Fuel Program

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Fuel Rod Behavior Leading to Core Coolability Concerns

- Experimental Database
  - Past experiments in US and Japan focused on fuel enthalpy above 280 cal/gm
    - » Molten fuel dispersal kinetics
    - » Mechanical energy generation from fuel-coolant interaction
  - Recent experiments in France and Japan at fuel enthalpy levels below 220 cal/gm
    - » Some failures resulted in dispersal of a small amount of pellet material coming from the pellet periphery as finely fragmented solid particles
    - » Measurable mechanical energy generation

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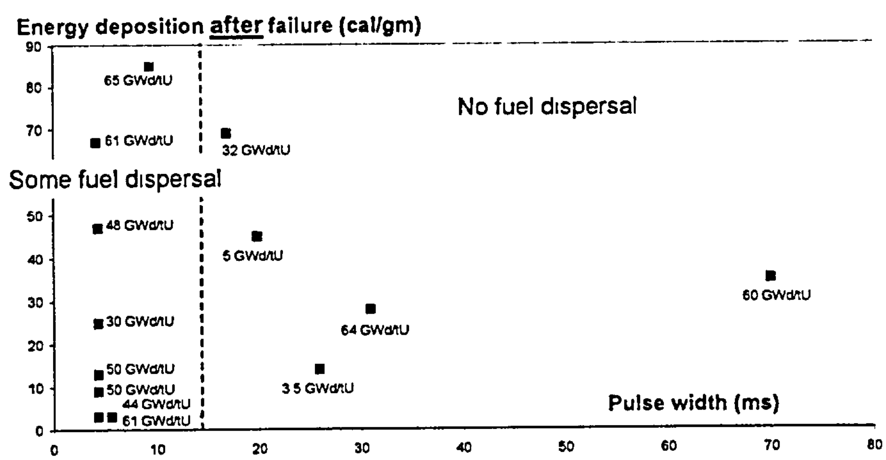
Current understanding of fuel dispersal and related core coolability issues

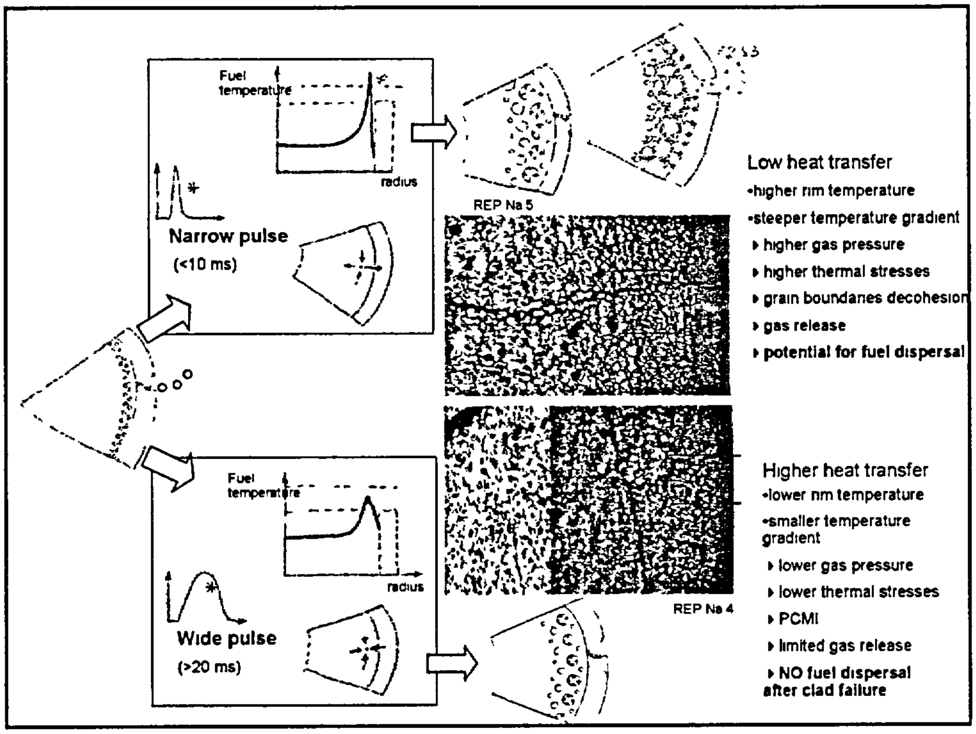
- Fuel particle dispersal during power pulse following cladding failure
  - Potential may increase above 40 GWd/T due to rim formation in fuel pellets
    - » Local peaking for burnup and fission density
  - Issues raised by fuel dispersal
    - » flow blockage and loss of rod geometry ?
    - » pressure pulse generation and threat on core geometry and pressure vessel integrity ?
- Data show that potential for fuel dispersal is a function of :
  - Energy deposition following cladding failure
  - Pulse width

EPRI

Pulse Width Effect on Fuel Dispersal



Note. Fuel dispersal observed only below 10 ms



EPRI

Post-Failure Behavior of High Burnup Fuel

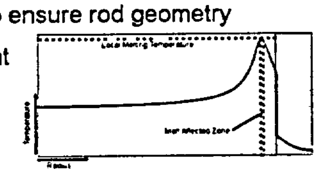
- No fuel dispersal is expected for prototypical pulse widths
- At high energy after failure, small amount of non-molten pellet material may be dispersed through failure opening but has low impact on:
  - Fuel rod geometry
    - » Experimental data (NSRR) show less then 10% of pellet material loss - mostly from rim region (1)
    - » Rod geometry is maintained in all cases (1) ➡
  - Fuel-coolant interaction (leading to pressure pulses)
    - » Tests exhibited low mechanical energy conversion (1)
      - temperature of dispersed material lower than UO_2 melting
      - involved limited amount of material (from rim region only)

(1) T Sugiyama and al "Mechanical energy generation during high burnup fuel failure under RIA conditions". Journal of Nuclear Sciences and Technology, Vol 37, No 10 October 2000

EPRI

Basis for Coolability Limit

- Establish fuel enthalpy limit to preclude incipient melting of the pellet
- Data show dispersal of molten fuel produce higher thermal to mechanical energy conversion ratios
  - Incipient melting in JMH-5 Test at 210 cal/gm and 30 GWd/tU show no adverse impact on fuel rod geometry
  - Analysis shows no adverse impact on the pressure vessel integrity
- To use incipient fuel melting as a precursor for coolability limit is very conservative
  - Maintains clad temperatures below melting to ensure rod geometry
  - Small region of high burnup fuel near incipient melting due to radial temperature peaking
    - » Majority of fuel well below peak temperature



  - Limits thermal to mechanical energy conversion ratio

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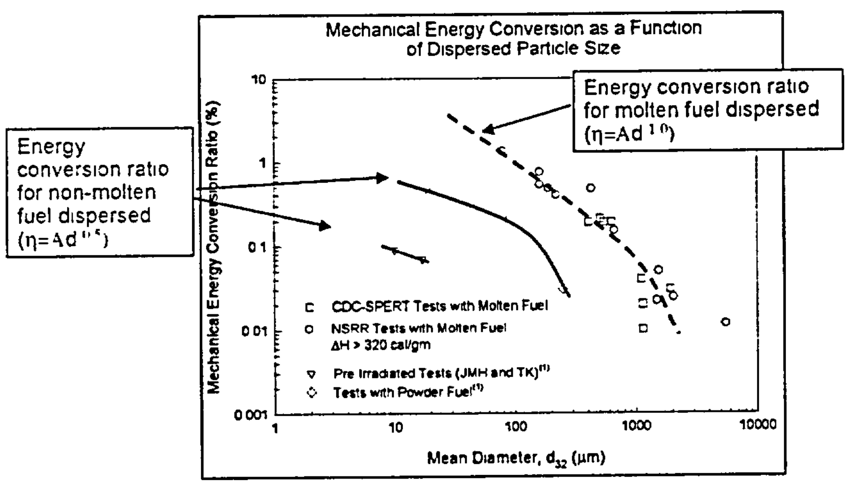
RIA Tests FCI Data



(1) T Sugiyama and al Journal of Nuclear Science and Technology, Vol 37, No 10 Oct 2000

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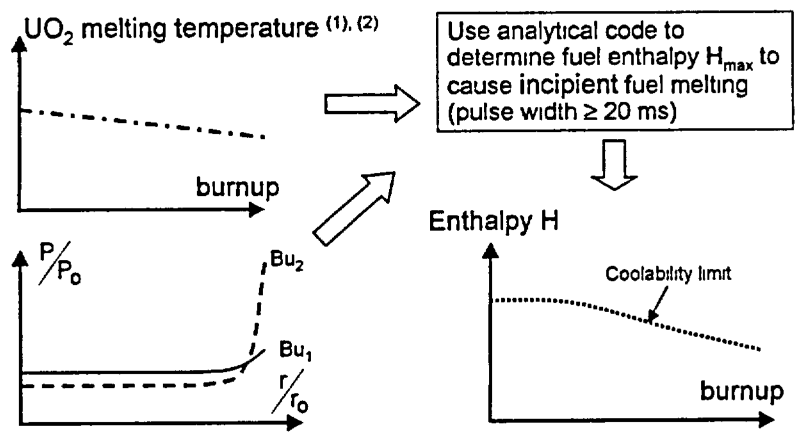
EPRI

Approach to develop RIA coolability limit based on energy to incipient fuel melting



(1) Y Philipponeau CEA technical Report LPCA n0 27

(2) J Komatsu and al Journal of Nuclear Materials n0 154, vol 38 (1988)

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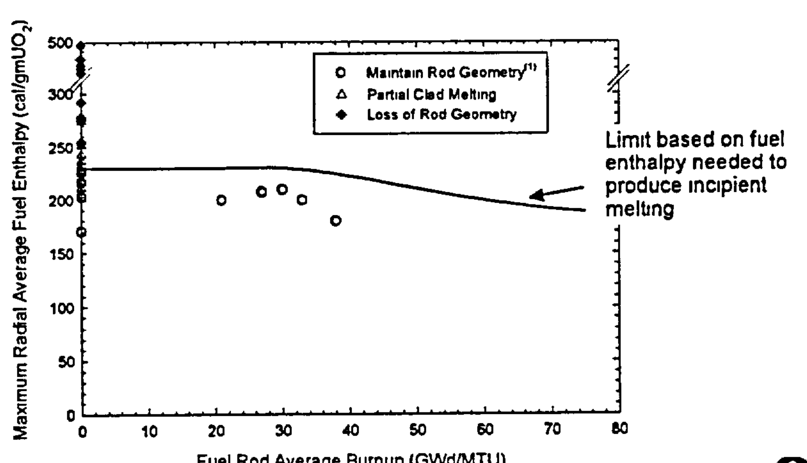
Comparison to High Energy Tests



(1) T Sugiyama and al Journal of Nuclear Science and Technology Vol 37, No 10 Oct 2000

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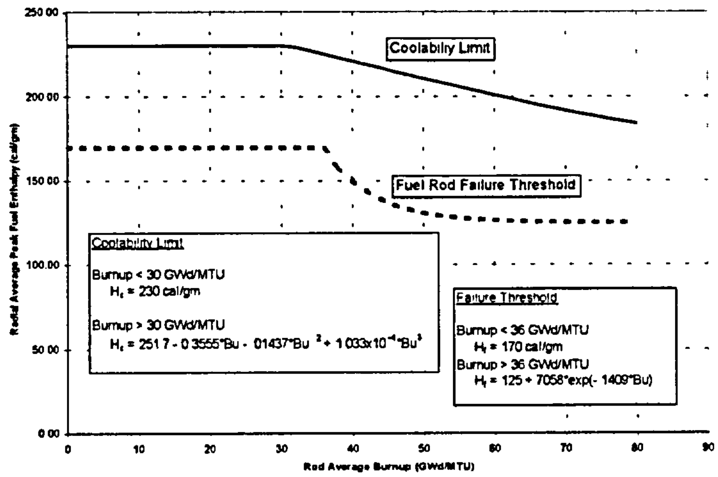
Revised RIA Acceptance Criteria



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EPRI

Summary (1)

- Revised clad failure threshold and core coolability limit as a function of burnup
  - Incorporates key controlling parameters
    - » Corrosion/hydriding evolution with burnup
    - » Burnup impact on UO_2 melting
- Criteria are given in terms of radial average peak fuel enthalpy
  - Applicable to HZP RIA
  - Use directly in core reload designs
  - Consistent with current practice
- DNB limit remains an acceptable criterion for at-power REA

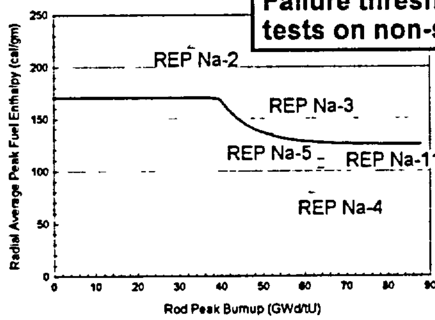
Robust Fuel Program

EPRI

Summary (2)

- Fuel Failure Threshold
  - Based on integral test results, mechanical property test data, and analytical approach
  - Represents a conservative lower bound for modern, low-corrosion cladding

Failure threshold bounds the data for tests on non-spalled Zr-4 rods



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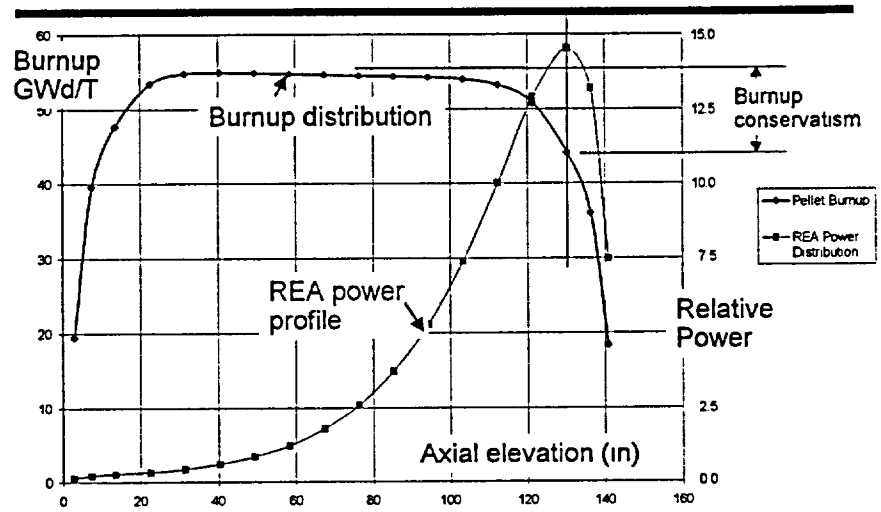
EPRI

Summary (3)

- Core Coolability Limit
  - No fuel dispersal expected under typical LWR conditions
  - However, fuel enthalpy limit established to minimize mechanical energy generation if fuel dispersal is assumed
    - » Limit peak fuel enthalpy to preclude incipient fuel melting
      - function of burnup
      - The limit is supported by data from both loss of rod geometry and mechanical energy release issues
    - » the limit is conservative
      - Small amount of fuel material involved (< 10%)
      - Large margin between burnup at peak power location during rod ejection and rod peak burnup used in UO_2 incipient melting calculation

Robust Fuel Program

Conservatism



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Robust Fuel Program

United States Nuclear Regulatory Commission

ANL LOCA-RELEVANT RESEARCH

H. H. Scott, NRC-RES

Y. Yan and M. C. Billone, ANL

NRC-ACRS Meeting
Rockville, MD
October 9, 2002

HIGH BURNUP LOCA FEATURES

- **BWR Fuel Rods (Limerick at ≈57 GWd/MTU, ≈10 μm OD Oxide)**
  - Effect of tight fuel-cladding bond and restricted gas flow on ballooning, burst, inner-surface-oxidation/hydrogen-pickup
  - Effect of irradiation on high temperature oxidation in steam
  - Effect of fuel-cladding mechanical interaction on fragmentation resistance during water quench; post-quench ductility
- **PWR Fuel Rods (HBR at ≈67 GWd/MTU, ≤ 100 μm OD Oxide)**
  - Similar fuel-cladding features as for BWR
  - Effect of in-reactor oxide layer on oxidation kinetics and ECR.
  - Effect of hydrogen pickup on oxidation kinetics, fragmentation-resistance during water quench and post-quench ductility

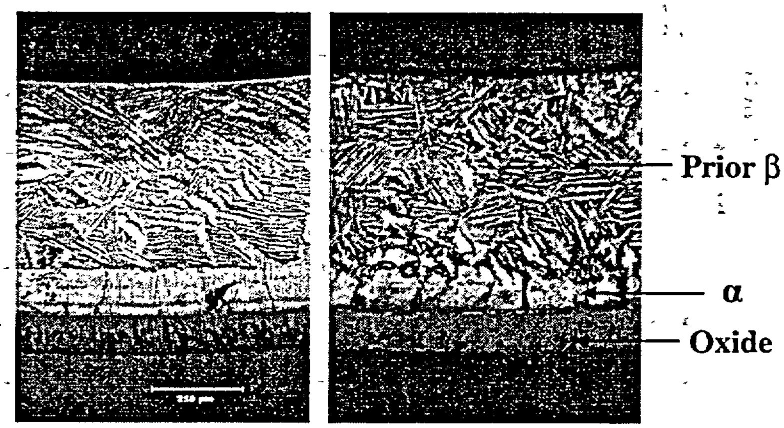
ANL LOCA-RELEVANT TESTS FOR HIGH BURNUP FUEL CLADDING

- **Steam Oxidation Kinetics Studies**
  - 900-1300°C, emphasis on 1204°C for 5-20 minutes
  - Kinetics of weight gain, (oxide + α) layer growth rate, effective β layer thickness vs. ECR
- **LOCA Integral Tests**
  - Test adequacy of 10CFR50.46 ECCS licensing criteria (ECR ≤ 17%, T ≤ 1204°C) for high burnup fuel
  - Determine ECR thresholds for thermal quench fragmentation and loss of post-quench ductility
- **Post-Quench Ductility Tests (Bend & Ring Compress.)**

SUMMARY OF HIGH-TEMPERATURE STEAM OXIDATION KINETICS RESULTS

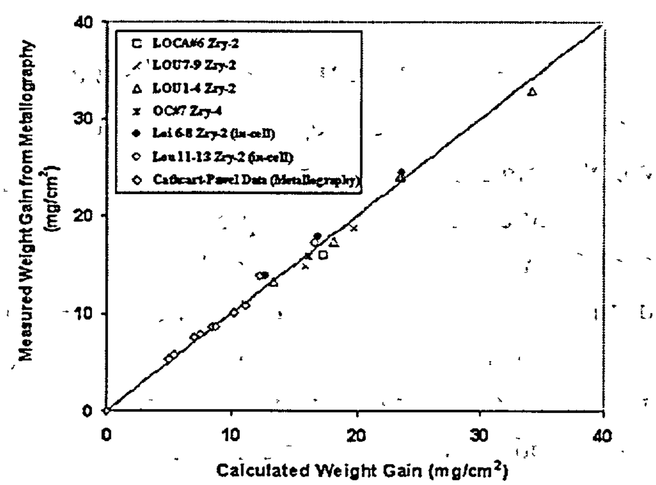
- **Metallographic Results for 1200°C Tests**
  - No difference in measured weight gain (Δw_m) for unirradiated and irradiated (10-µm pre-test oxide layer) Zry-2 and unirradiated Zry-4
  - Excellent agreement between measured Δw_m and Cathcart-Pawel (CP) model predictions (Δw_p)
  - CP Δw_p is good "best-estimate" correlation for Zry-2, Zry-4, ZIRLO, M5 and E110 at 1100-1500°C
- **Metallographic Analysis for 1000-1100°C Test Samples** (in progress)

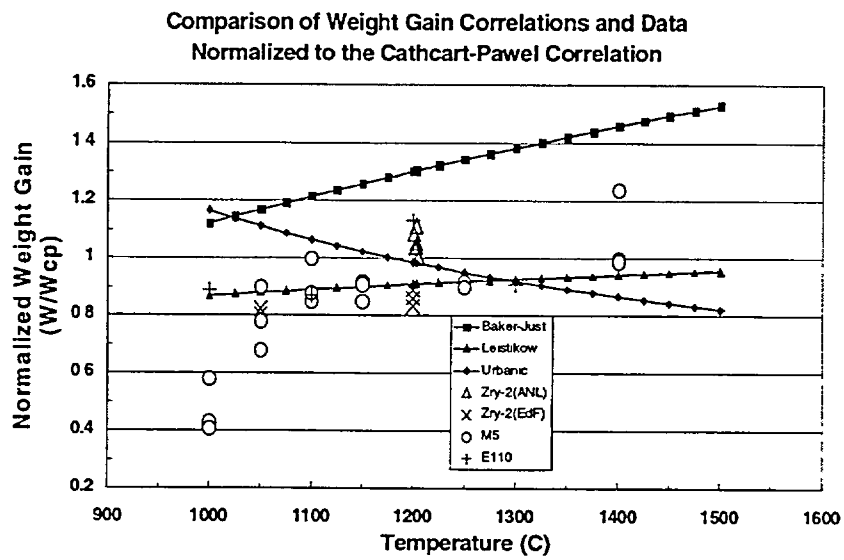
Oxide, α and β Layer Characteristics (in Steam at 1204°C for 10 Minutes)



unirradiated Zry-2 irradiated Zry-2

Measured Weight Gain from Metallography for Irradiated and Unirradiated Zry-2 and Zry-4





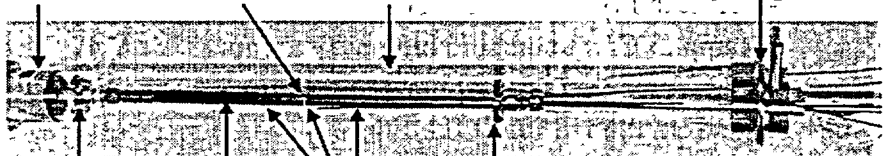
SUMMARY OF STEAM OXIDATION KINETICS RESULTS (Cont'd)

- **Assessment of Cathcart-Pawel Models**
  - CP model based on very rapid heating and cooling rates
  - Weight gain correlation is good even for slow ramp rates
  - Underpredicts α-layer and overpredicts β-layer thickness for LOCA-relevant cooling rates (1-8°C/s) due to oxygen diffusion from β to α phases during 1200°C → 800°C
  - ANL results at ≈5°C/s cooldown from 1200°C to 800°C
  - Impact is TBD as "ductility" increases with reduction in oxygen and decreases with thickness reduction

LOCA INTEGRAL TESTING SCOPE

- **Parameters Common to BWR and PWR Tests**
  - Fuel-cladding samples = 305-mm long; fueled region = 270 mm
  - PCT = 1204±20°C, temperature ramps relevant to SB-LB LOCA
  - Internal pressure P_i<1.3×system pressure, plenum V = 5 to 10 cc
  - Best-estimate 17% ≤ ECR < ≈30% → oxidation time ≈2-10 min.
- **High Burnup BWR Rods (Limerick)**
  - Temperature ramp rate = 5°C/s (2.5-7°C/s for SB-to-LB LOCA)
  - Cladding $\Delta P = P_i - P_s \leq$ 8.6 MPa [6.7 MPa (SB)- 8.6 MPa (LB)]
- **High Burnup PWR Rods (H. B. Robinson)**
  - Temperature ramp rate = 5°C/s (1-2°C/s for SB, 7-10°C/s for LB)
  - Cladding $\Delta P = P_i - P_s <$ 20 MPa [P_s = 3.4 → 0.2 MPa (SB → LB)]

LOCA TEST TRAIN ASSEMBLY



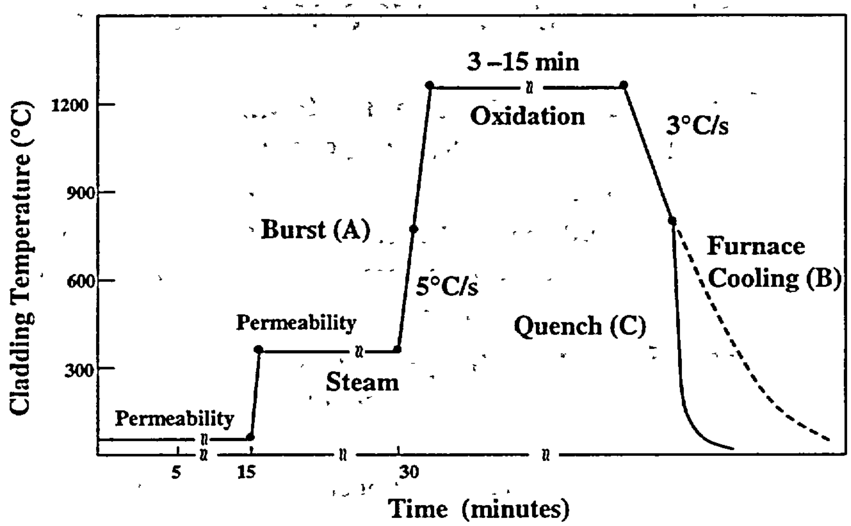
LOCA INTEGRAL TESTING SCOPE (Continued)

- **Steam and Quench Water Flow-rates/Volume**
  - Steam flow = 5-10 g/minute
  - Cool-down rate = 3°C/s from 1204°C to 800°C (1-8°C/s for BWR)
  - Quench water velocity = 5 mm/s (initiated at 800°C)
- **Test Times at 1204°C**
  - Maximum ECR depends on wall thinning and extent of double-sided oxidation
  - First test will be run for 5 minutes at 1204°C

LOCA INTEGRAL TEST SEQUENCE FOR FIRST SERIES OF BWR TESTS

- **Phase A: Fuel Permeability, Ballooning and Burst**
  - Permeability at 30°C and 300°C
  - Ramp (5°C/s) to burst in high purity argon
  - Slow furnace cool from burst temperature
- **Phase B: Above Plus Oxidation**
  - Permeability (30°C and 300°C); ramp to 1204°C in steam
  - Hold (5 min.) at 1204°C; cool to 800°C at 3°C/s
  - Slow furnace cool from 800°C to RT
- **Phase C: Above Plus Quench at 800°C**
  - Repeat B through cooling to 800°C; quench at800°C

LOCA INTEGRAL TEST SEQUENCE



SUMMARY OF OUT-OF-CELL LOCA INTEGRAL TEST RESULTS

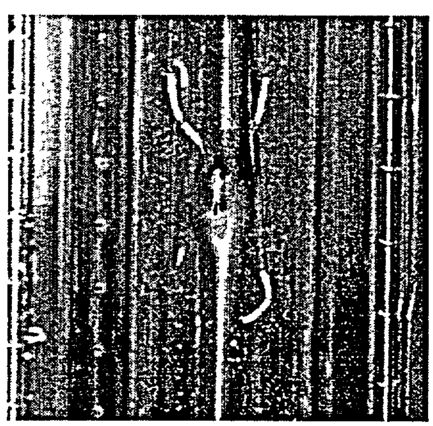
- **Test Specimens and Conditions**
  - Specimens: GE-11 (9×9) Zry-2 cladding (0.71-mm wall), zirconia pellets with 0.1-mm radial gap, 10-cm^3 void volume above pellets
  - Conditions: cladding ΔP = 8.62 MPa at RT
- **Test #3 Results (10 min. in steam at 1204°C)**
  - Peak ΔP = 9.31 MPa, burst $\Delta P \geq$ 8.41 MPa, burst T ≈ 760°C
  - "Dog-bone-shaped" burst opening; ≈13-mm long
  - Peak $\Delta D/Do$ ≈ 45%; axial extent of balloon ≤130 mm
  - Specimen survived thermal quench & post-quench handling

SUMMARY OF OUT-OF-CELL LOCA INTEGRAL TEST RESULTS (Cont'd)

- **Test #4 Results(10 min. in steam at 1204°C)**
  - Peak ΔP = 10.28 MPa, burst ΔP ≥ 9.42 MPa, burst T ≈ 720°C
  - Similar burst opening and ballooning strain as in Test #3
  - Sample failed across mid-burst region at 100°C after quench
  - Based on results, future specimens will be pressurized at 300°C and time at 1204°C will be < 10 min.
- **Test #5 Results(ramped to burst in Ar)**
  - Peak ΔP = 8.95 MPa, burst ΔP ≥ 8.61 MPa, burst T ≈ 732°C
  - "Dog-bone-shaped" burst opening; ≈13-mm long; 2-mm wide
  - Peak ΔD/Do ≈ 44%; axial extent of balloon ≈100-mm long

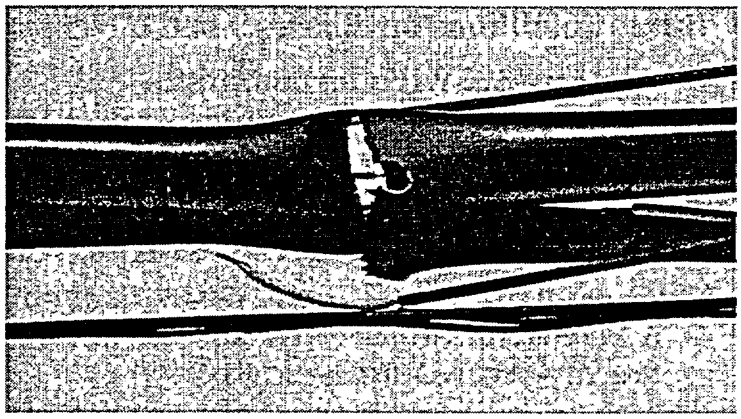
Out-Cell Test 3: 10 min. at 1204°C, C-P ECR = 38%

(Survived quench & post-quench handling)



Out-of-cell Test 4: 10 min. at 1204°C, C-P ECR = 38%

(Survived quench; fractured at 100°C under dead-weight load)

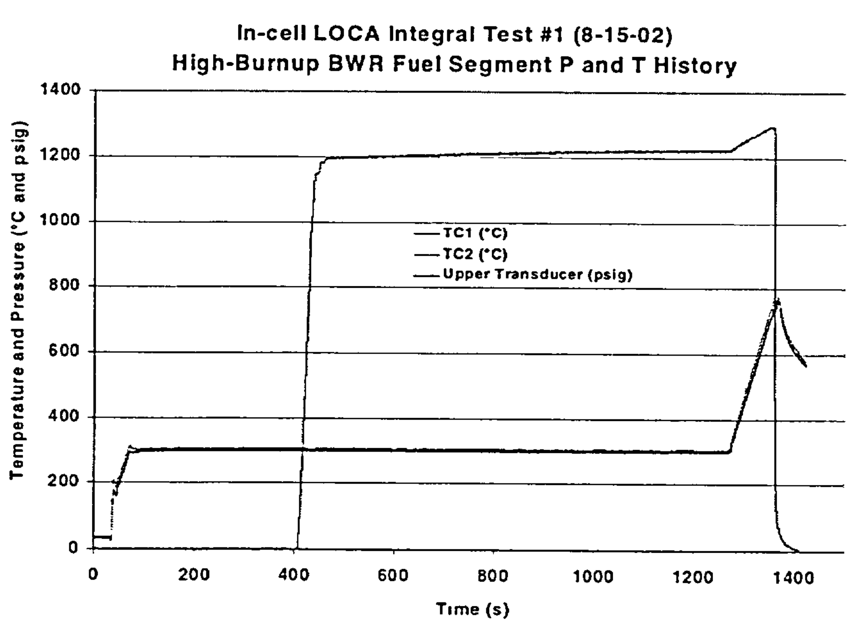


1st LOCA INTEGRAL TEST RESULTS
LIMERICK HIGH-BURNUP BWR PHASE A

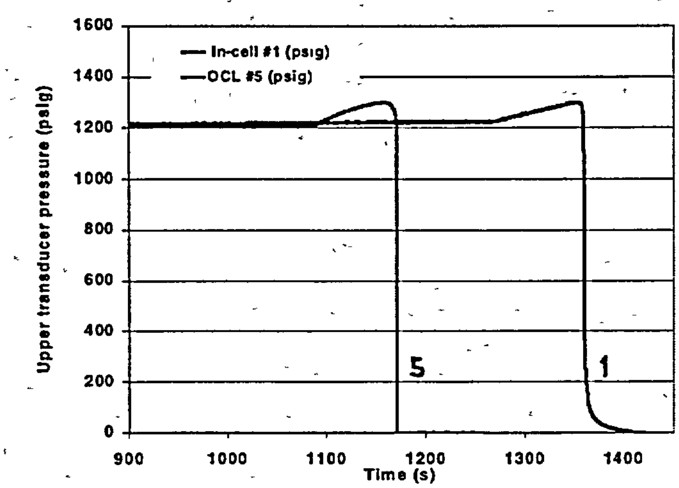
- **Limerick Specimens Prepared**
  - Phase A: middle of Grid Span #5; 0.46-0.76 m above fuel MP
  - Phase B: middle of Grid Span #6; 0.94-1.24 m above fuel MP
  - Phase C: to be prepared from GS #5 & 6 of different rod
- **Phase A Test (Completed on 08-15-02)**
  - Calibration of top pressure transducer at RT from 0-10 MPa
  - Pressurize top of specimen with He to 8.38 MPa at 300°C
  - Stabilize (pressure rose to 8.56 MPa over 15 min) at 300°C
  - Ramp temperature to burst in Ar; slow furnace cool

1^{st} LOCA INTEGRAL TEST RESULTS LIMERICK HIGH-BURNUP BWR PHASE A (Cont'd)

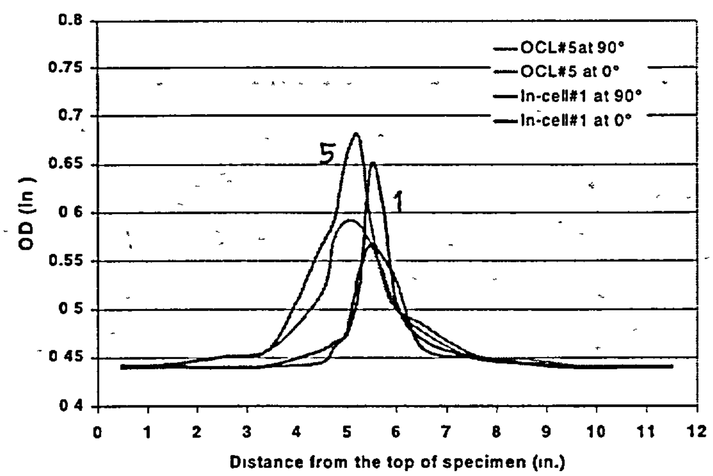
- **Burst Conditions for Phase A vs. OCT#5**
- **Peak ΔP = 8.95 MPa for both tests**
  - Burst ΔP=8.61 MPa at 755°C (vs. 8.26 MPa at 732°C for OCT#5)
  - Burst shape is oval (vs. dog-bone for OCT#5)
  - Burst length (≈12-13 mm) and max. opening (2-3 mm) for both
- **Balloon Characteristics for Phase A vs. OCT#5**
  - Average $\Delta D/D_o$ at burst center = 38% (vs. 44% for OCT#5)
  - Axial extent of balloon = 50 mm (vs. 100 mm for OCT#5)
  - Note: $\Delta T_\theta \approx$ 30°C (vs. ≈10°C for OCT#5)



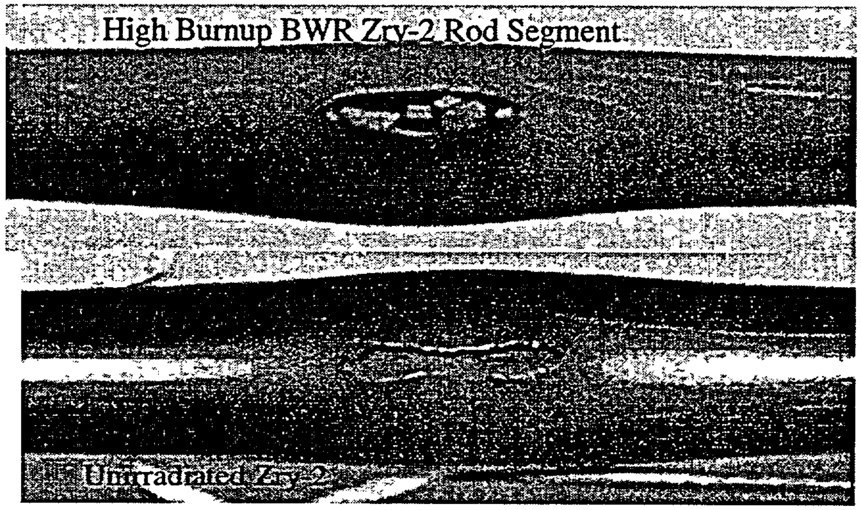
PRESSURE HISTORIES FOR IN-CELL TEST #1 AND OUT-OF-CELL TEST #5



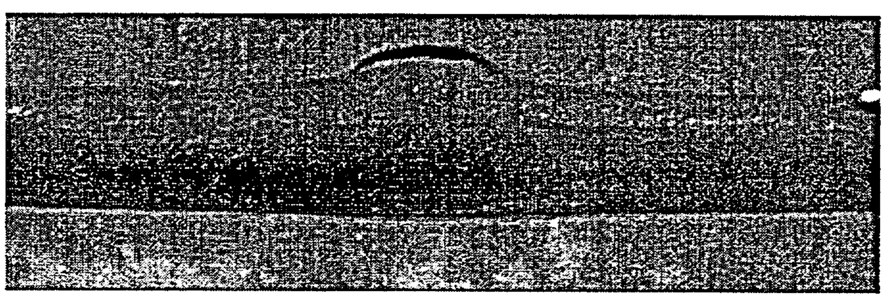
BALLOONING COMPARISON IN-CELL TEST #1 vs. OUT-OF-CELL TEST#5



BURST OPENING COMPARISON



SIDE VIEW OF HIGH-BURNUP BWR ROD SEGMENT AFTER LOCA PHASE A TEST



FUEL BEHAVIOR DURING AND AFTER HIGH-BURNUP BWR LOCA TEST #1

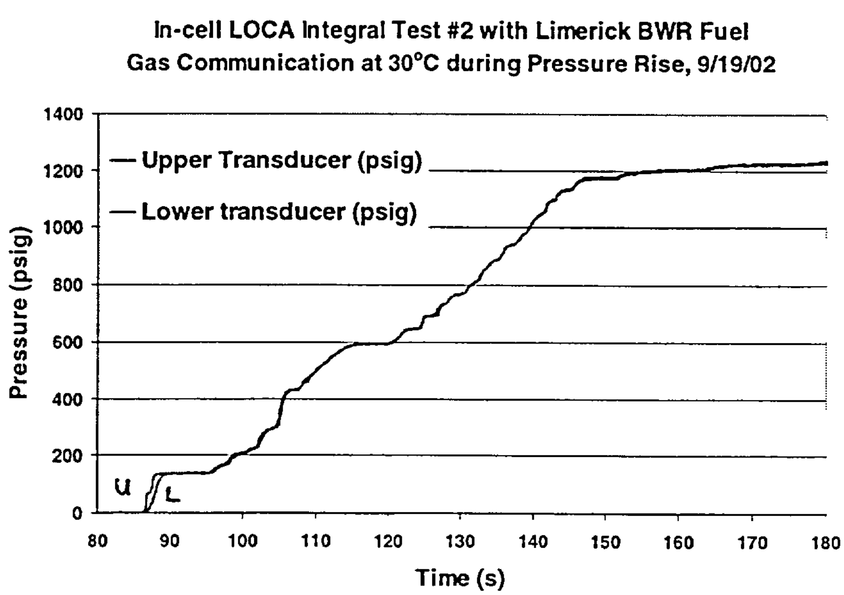
- **Dark Deposit on Quartz Tube**
  - Black deposit on tube (will be gamma-scanned, Cs??)
  - Probably occurred during burst
  - Extends from burst region to about 50 mm above burst
- **Fuel Particle Fallout during Post-Test Handling**
  - Test train was moved from vertical position in furnace to horizontal position at a different workstation
  - Large number of small fuel particles (5.2 g) fell out of burst opening during rotation of specimen from vertical to horizontal and about longitudinal axis

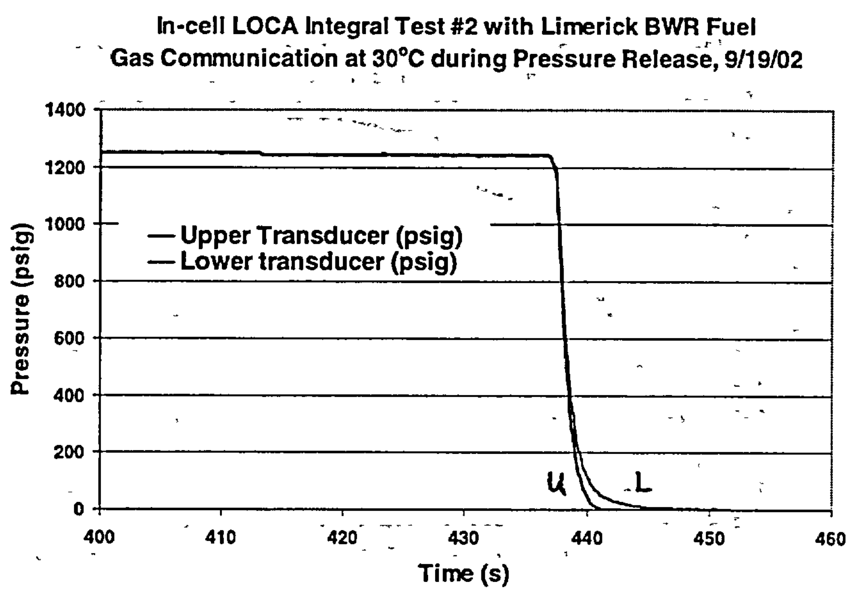
FUEL DEPOSIT AND PARTICLES WITHIN QUARTZ TUBE

Black Deposit Cs Compound?? **Fuel Particles**

2nd LOCA INTEGRAL TEST RESULTS
HIGH-BURNUP BWR PHASE B

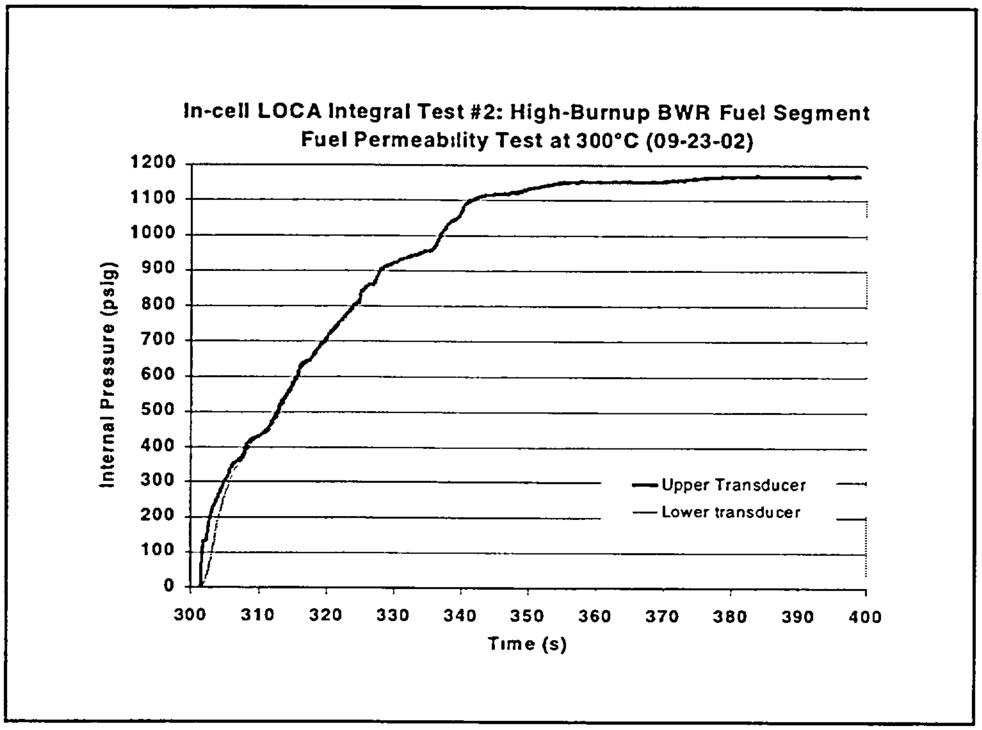
- **Permeability Results at 30°C**
  - Pressurization ramp at top of specimen to 8.7 MPa
    Excellent gas communication from 1 to 8.7 MPa
    Small axial pressure drop ($\Delta P_z \leq 0.5$ MPa) for 0-4s
  - Rapid pressure release at top of specimen (valve open)
    Lag in lower pressure response ($\Delta P_z \leq 0.6$ MPa)
    Slow release from bottom transducer from 2→0.1 MPa
  - Results are consistent with fuel microstructure
    Macrocracks; extensive microcracks in outer fuel zone
    Note: 20% fission gas release during irradiation

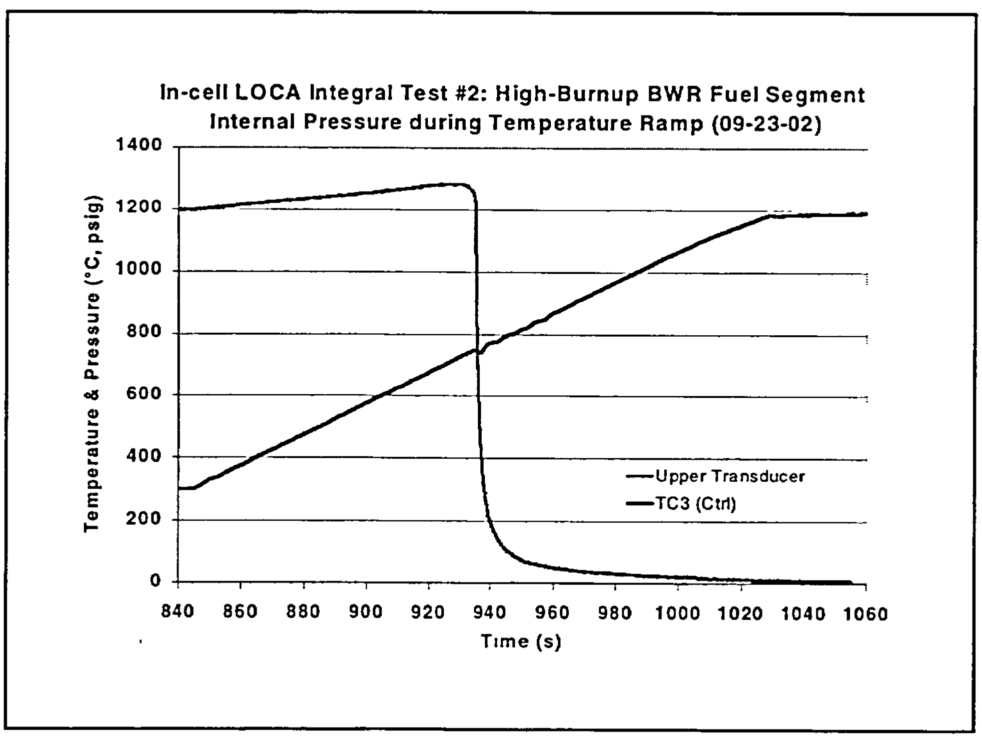




2nd LOCA INTEGRAL TEST RESULTS HIGH-BURNUP BWR PHASE B (Cont'd)

- **Permeability Results at 300°C**
  - Pressurization ramp at top of specimen to 8.0 MPa
  - Excellent gas communication from 2 to 8 MPa
  - Some axial pressure drop ($\Delta P_z \leq 0.9$ MPa) for 0-4s
  - Pressure increases to 8.4 MPa during 300°C hold
- **Temperature Ramp to 1204°C**
  - Pressure peaks at 9.0 MPa at 728°C
  - Burst at 750°C and ≈8.4 MPa (1200 psig)
  - Rapid drop to 3.5 MPa; slow drop from 3 → 0.1 MPa

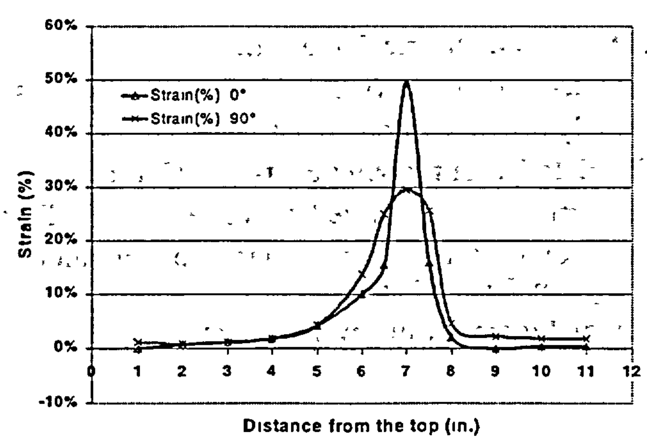

In-cell LOCA Integral Test #2: High-Burnup BWR Fuel Segment
Fuel Permeability Test at 300°C (09-23-02)
Internal Pressure (psig)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
300
310
320
330
340
350
360
370
380
390
400
Time (s)
Upper Transducer
Lower transducer


In-cell LOCA Integral Test #2: High-Burnup BWR Fuel Segment
Internal Pressure during Temperature Ramp (09-23-02)
Temperature & Pressure (°C, psig)
1400
1200
1000
800
600
400
200
0
840
860
880
900
920
940
960
980
1000
1020
1040
1060
Time (s)
Upper Transducer
TC3 (Ctrl)

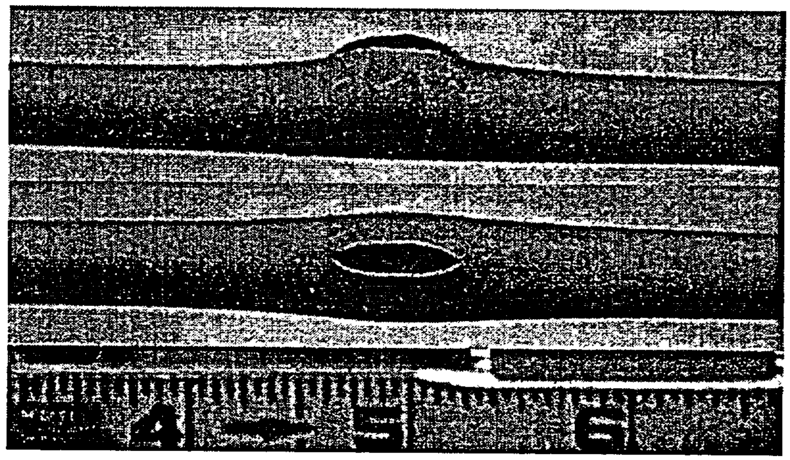
2nd LOCA INTEGRAL TEST RESULTS HIGH-BURNUP BWR PHASE B (Cont'd)

- **Ballooning**
  - Axial extent ≈100 mm, peak at 25 mm below midplane
  - Max. $\Delta D/D_o$ = 49%; max. average strain = 39%
  - Uncorrected for oxide thickness
- **Burst Opening**
  - Oval-shaped
  - 14-mm long; 3.5-mm maximum width

2ND LOCA INTEGRAL TEST WITH HIGH-BURNUP BWR ROD: PROFILOMETRY



LOCA INTEGRAL TEST (PHASE B) HIGH-BURNUP BWR BALLOON & BURST



FUEL BEHAVIOR DURING AND AFTER HIGH-BURNUP BWR LOCA TEST #2

- **Dark Deposit on Quartz Tube (same as in Test 1)**
  - Black deposit on tube (will be gamma-scanned, Cs??)
  - Probably occurred during burst
- **Fuel Particle Fallout during Post-Test Handling**
  - Fuel particles (<1 g) ejected during test were collected
  - Bottom of test train was capped to trap fuel fallout during transfer and handling
  - Total of 4 grams of fuel were collected

LOCA INTEGRAL TEST (PHASE B) HIGH-BURNUP BWR FUEL PARTICLES

Fuel Particles (4 g) ≈15% Released during Test; ≈85% Released during Transfer

30×30 mm Jar Cross-section

NEAR TERM LOCA WORK

- **Verify Specimen Preparation Techniques**
  - Six-inch "practice"sample and bottom of Test #1 sample
  - Metallographic examinations
- **Determine Composition of Dark Deposit on Quartz Tube (Gamma Scanning)**
- **Determine Max. ECR and H Distribution for 5-min. Tests (in-cell & out-of-cell) at 1204°C**
- **Move Quench System In Cell and Run Full LOCA Sequence (11-02)**

United States Nuclear Regulatory Commission

ANALYSIS OF RIA AND ATWS EVENTS

Ralph Meyer
Office of Nuclear Regulatory Research

ACRS Subcommittee
October 9, 2002

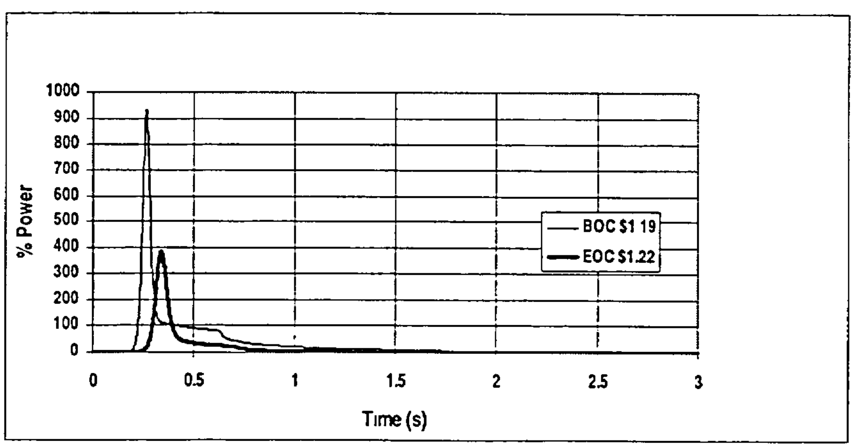
REACTIVITY-INITIATED ACCIDENTS (RIA) [Unassembled Pieces of the Puzzle]

- Summarize Pulse Width Situation
- Show Vitanza Correlation
- Describe Method for Making Temperature Corrections

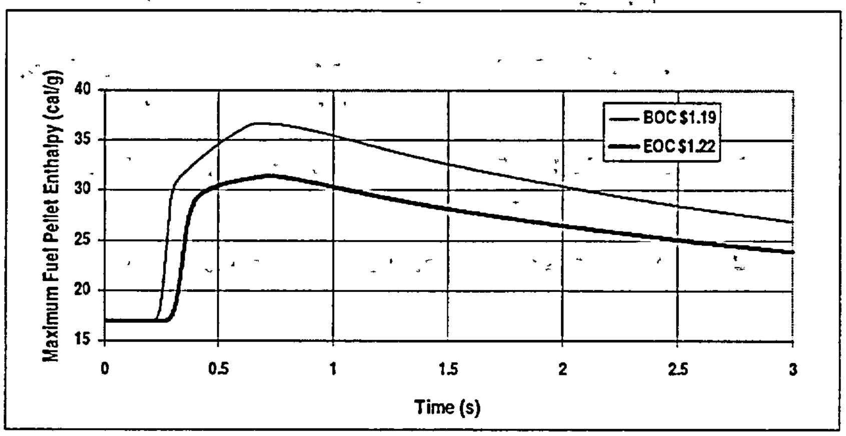
BNL CALCULATIONS OF PULSE WIDTH

- PWR Rod-Ejection Accident (REA)
- PWR Boron-Dilution Accident
- BWR Rod-Drop Accident (RDA)

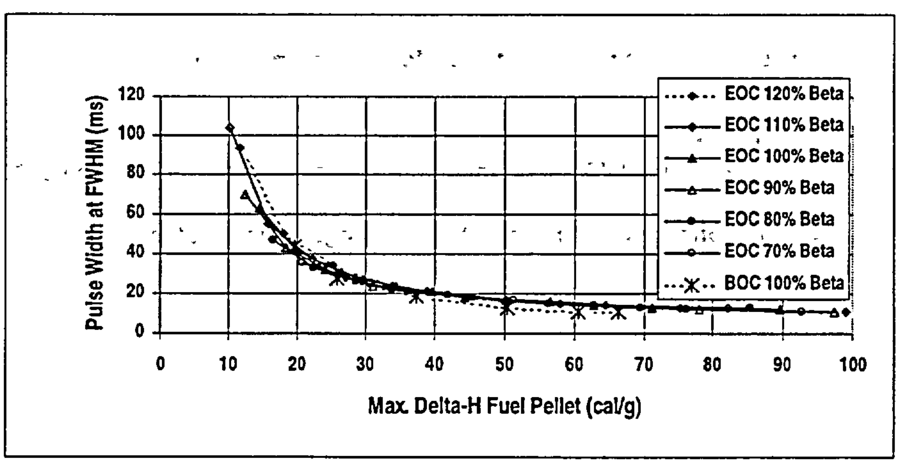
POWER DURING AN REA



MAXIMUM LOCAL FUEL (PELLET AVG) ENTHALPY



PULSE WIDTH VS MAX CHANGE IN LOCAL FUEL ENTHALPY



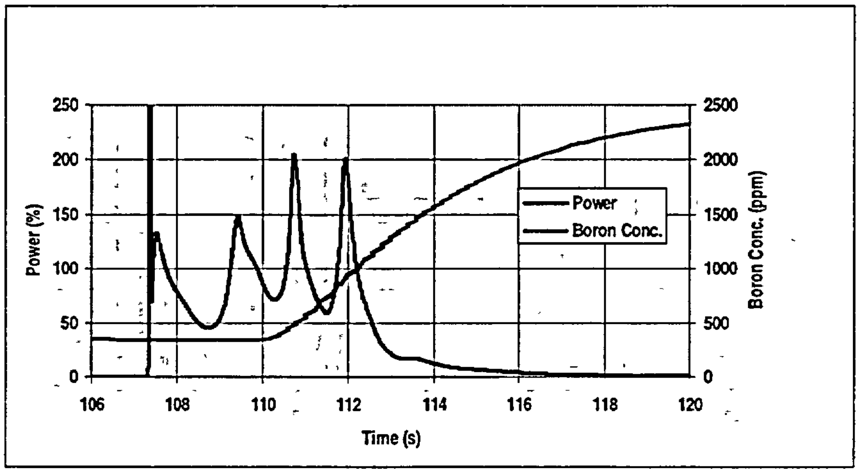
CONCLUSIONS FOR REA

- General trends are in agreement with analytical model
- Pulse width is 25-100 ms as energy deposition goes from 30 to 10 cal/g; range for most likely prompt-critical REAs
- Pulse width is 10-15 ms for energy depositions (fuel enthalpy change) of 60-100 cal/g
  - If testing limits of fuel, use these short pulse widths

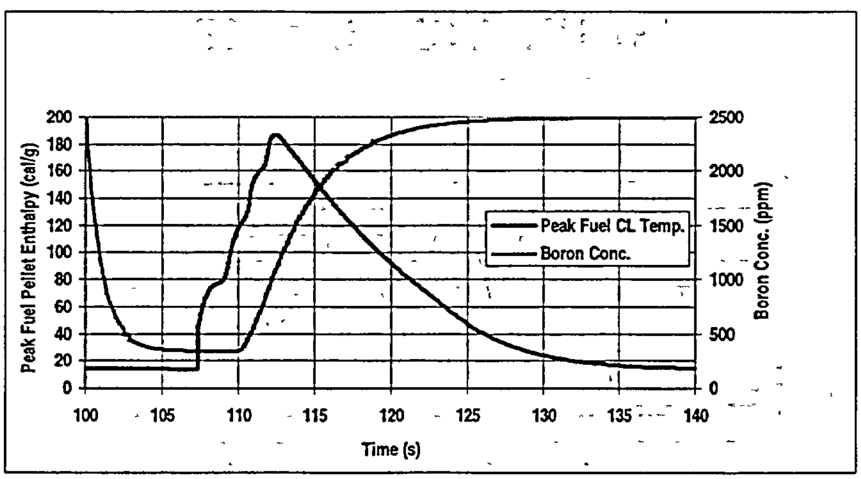
PULSE WIDTH FOR BORON DILUTION EVENT

- Worst case considered at BNL for 25% pump start
- Initial power spike most severe
  - Pulse width 20-40 ms corresponding to peak enthalpy increase of 30-15 cal/g
  - Additional power spikes with much longer pulse widths

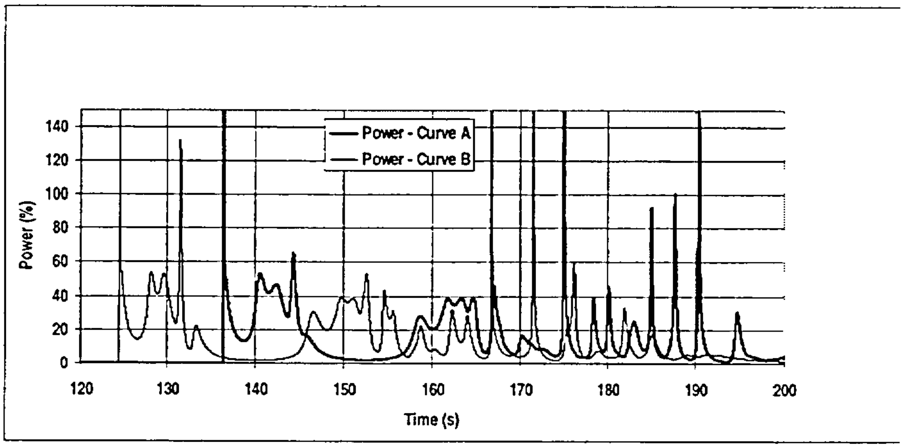
BORON DILUTION WITH PUMP ON



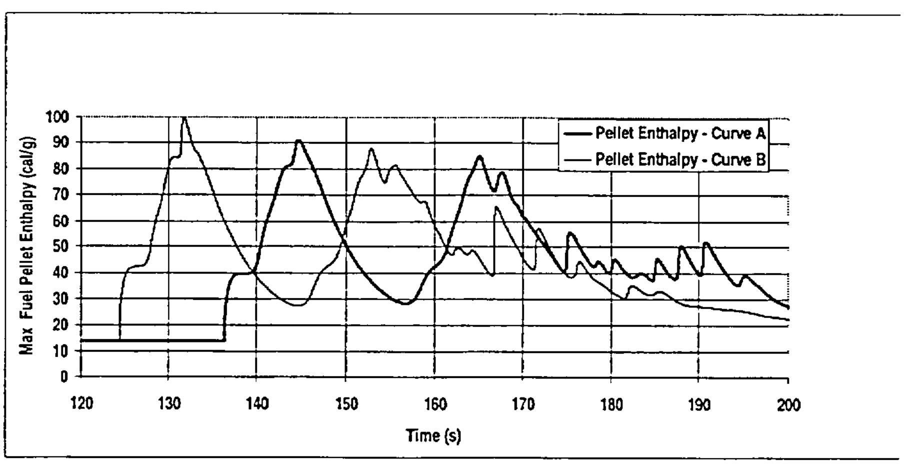
PEAK PELLET-AVERAGE ENTHALPY



BORON DILUTION - POWER UNDER NATURAL CIRCULATION CONDITIONS



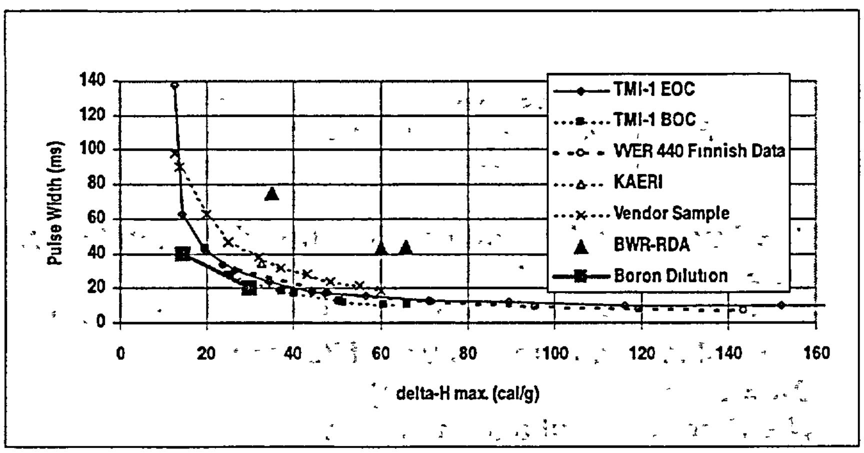
BORON DILUTION – PEAK FUEL ENTHALPY UNDER NATURAL CIRCULATION CONDITIONS



BWR ROD DROP ACCIDENT (RDA)

- Previous analysis by BNL et al. substantial but pulse width not usually given or measurable from power vs time paper plots
- Data points (limited number) suggest pulse widths longer than for PWRs
  - In part due to longer neutron lifetime (average time needed for a fission neutron to cause another fission—$P \sim P_0 \exp(at/\ell)$ where a depends on reactivity and ℓ is the lifetime)

PULSE WIDTH FROM PWR AND BWR ANALYSIS OF DIFFERENT RIAs



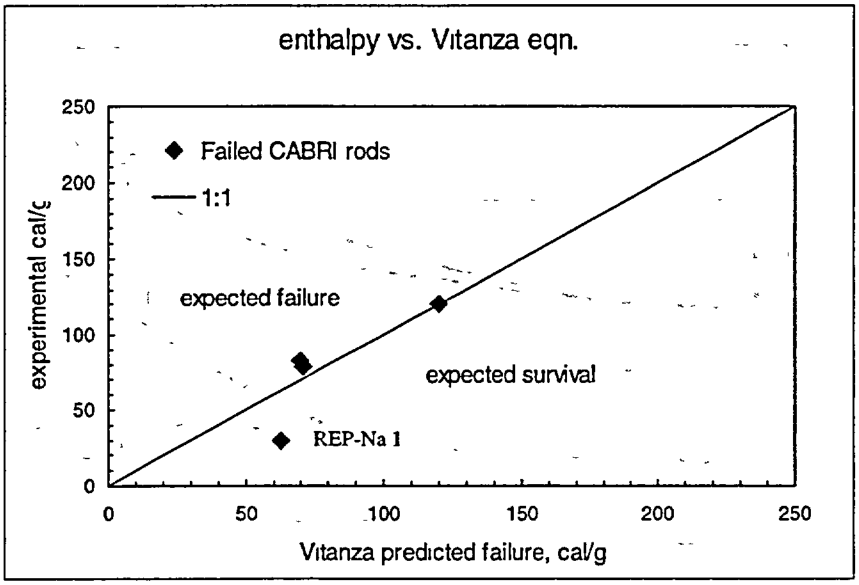
POTENTIAL EMPIRICAL CORRELATION FOR CLADDING FAILURE

[Improvements needed]

Correlation for the RIA Failure Threshold (Vitanza 2001)

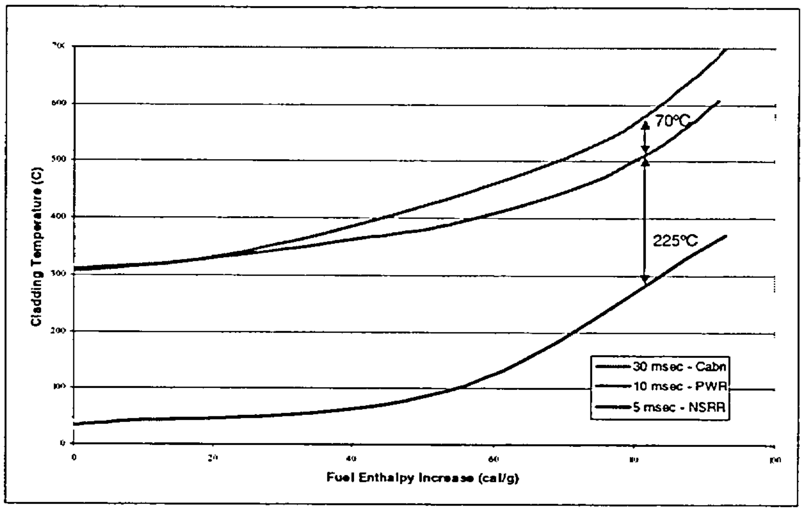
$$H_F = \left[200 \cdot \frac{25+10D}{Bu} + 0.3\Delta\tau\right]\left(1 - \frac{0.85OX}{W}\right)^2$$

H_F = Fuel Enthalpy Failure Limit (maximum of 200 cal/g)
Bu = Burnup in MWd/kg
D = 0% (brittle) to 1% (ductile) cladding hoop strain limit
$\Delta\tau$ = Pulse Width (maximum of 75 msec)
OX = Oxide thickness in (um)
W = Cladding wall thickness (um)

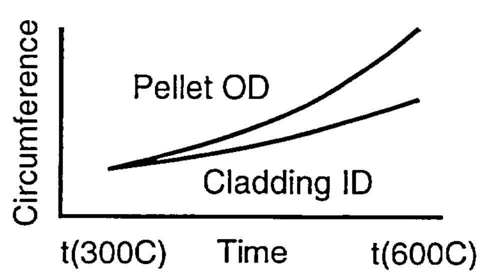


POSSIBLE PULSE-WIDTH EFFECTS

- Cladding Temperature Differences
  - Mechanical Properties
  - Thermal Expansion
- Dynamic Fission Gas Expansion

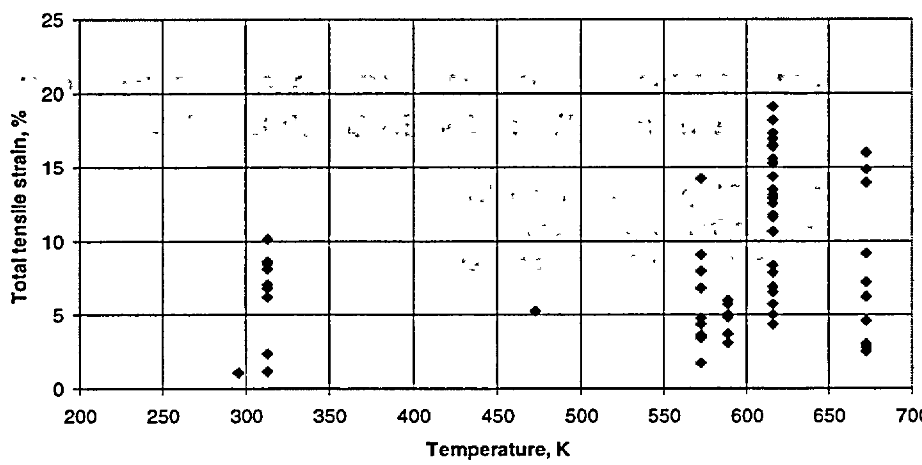


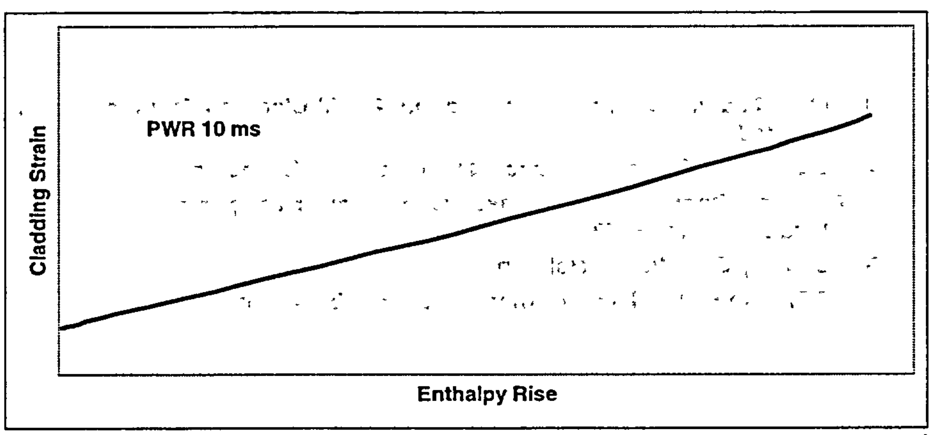
Cladding Temperature (C)
Fuel Enthalpy Increase (cal/g)
70°C
225°C
30 msec - Cabri
10 msec - PWR
5 msec - NSRR



Circumference
Pellet OD
Cladding ID
t(300C)
Time
t(600C)

Total tensile strain vs temperature K





SOME PROGRESS ON ANALYZING FUEL BEHAVIOR DURING BWR POWER OSCILLATIONS

- PIRT Implications (reminder)
- Data from Japan (new)
- Codes from Finland (progress)

IMPLICATIONS FROM POWER-OSCILLATION PIRT

(ACRS Subcommittee, April 4, 2001)

- Pellet-Cladding Mechanical Interaction (PCMI) Cladding Failures are not Expected
- LOCA-like Oxidation is Expected with possible Ballooning and Rupture
- Cladding Embrittlement will take place at Lower Temperature than Cladding Melting or Fuel Melting
- Runaway Oxidation is Not Expected
- LOCA-like Embrittlement Criteria appear to be Appropriate

A METHOD TO RESOLVE POWER-OSCILLATION ISSUES

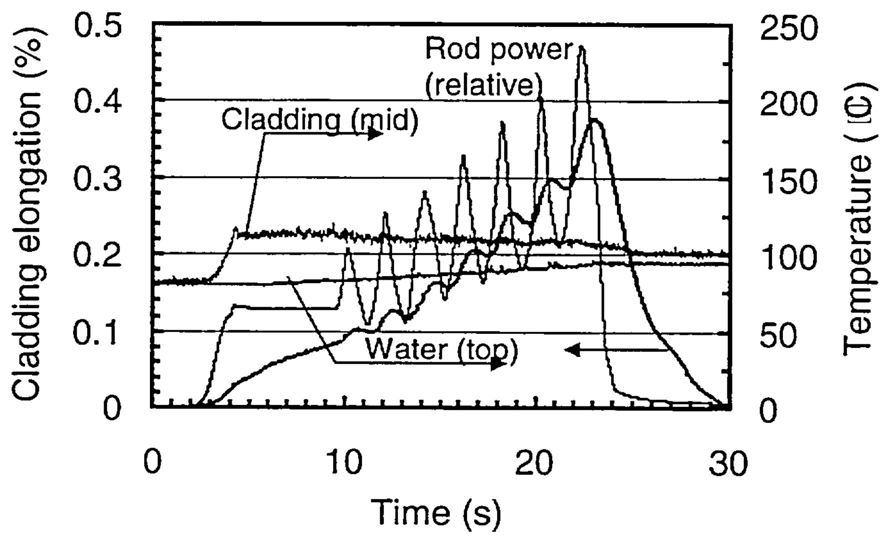
(ACRS Subcommittee, April 4, 2001)

- Repeated-Pulse Test Capability in NSRR to address PCMI Failure
- High Temperature Dryout Test Capability in Halden Reactor
- Information from LOCA Work on Embrittlement Criteria
- Generic Calculations with FRAPTRAN-GENFLO (STUK Finland) Hot Channel Code to compare with Embrittlement Criteria

Target 2004 for Confirmatory Resolution at 62 GWd/t. Depends on Testing that has not been Fully Planned and future Code Developments.

NEW JAERI DATA TO BE PRESENTED AT NSRC-2002

- Two tests performed on BWR rods with 25 and 56 GWd/t burnup
- PCMI not enhanced by cyclic loads (i.e., no ratchet effect)
- Results not fully analyzed (by NRC, anyway)



FRAPTRAN-GENFLO CODE ANALYSIS

- Coupled codes installed at PNNL in early September 2002
- Sample cases have been run by PNNL and NRC staff
- Analytical plan to be developed in 2003

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CREEP TESTING OF SPENT FUEL RODS IN DRY STORAGE

By
Sudhamay Basu
Office of Nuclear Regulatory Research

Presentation for
ACRS Fuel Subcommittee Meeting
October 9, 2002

Program Scope

- Post-storage characterization of spent fuel rods
  - profilometry
  - fission gas analysis
  - oxide and hydride, hydrogen content
  - mechanical properties (tensile, microhardness)
- Creep testing of fuel rods
- Post-creep mechanical properties
  - tensile
  - ductility
- Medium (≤45 GWd/MTU) and high burnup cladding
- Focus of presentation - testing of PWR (Surry) fuel rods
  - average rod burnup of 36 GWd/MTU
  - rods in spent fuel pool ~5 years
  - rods stored in dry cask since 1985

Regulatory Issues

- License renewal of existing dry casks for storing spent nuclear fuel
  - applications expected as early as 2004
  - cask integrity for continued storage (additional 20 to 100 years) important for safe storage under normal and accident conditions
- Licensing new casks for storage and transport of high burnup fuel
  - power plants to discharge more high burnup (>45 GWd/MTU) fuel
  - spent fuel pools to loose full core reserve capacity
  - timely licensing important for safe storage and transport
- Spent fuel in dry casks must be protected from degradation that leads to gross ruptures (10CFR Part 72)
- Creep and mechanical properties data required for spent fuel cladding in long-term storage
- For high burnup fuel, technical basis required to demonstrate validity of Part 72 requirements

Post-Storage Characterization

- Profilometry data
  - diameter changes ~0.6%, very little variation
  - thermal creep during storage <0.1%
- Gas analysis data
  - fission gas release 0.4 to 1.0% - within range
  - internal gas pressure ~3.5 MPa - within range
- Metallography data
  - OD oxide layer thickness ~20 - 40 μm
  - hydrogen content ~200 - 300 wppm
  - no hydride reorientation
- Mechanical properties data
  - post-storage microhardness ~240 DPH (no annealing)
  - creep tests
  - tensile tests

Surry Creep Test Matrix

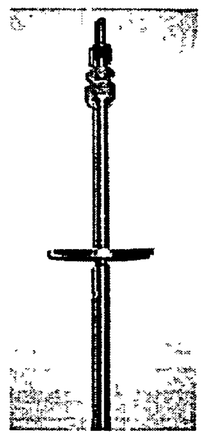
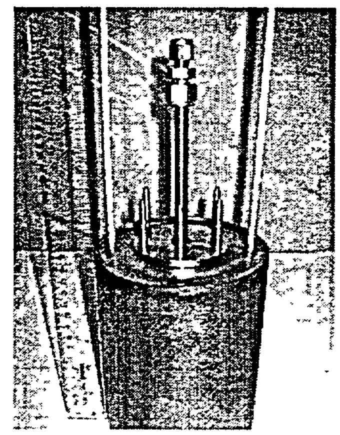
Test No.	Temp. (°C)	Stress (MPa)	Purpose
1	380	220	primary/secondary creep, residual creep strain
2	380	190	primary/secondary creep
3	400	190	primary/secondary creep
4	400	250	primary/secondary creep, residual creep strain
5	360	220	primary/secondary creep
6	400	160	primary/secondary creep
7	400	220	primary/secondary creep, residual creep strain

Test Description

- Specimen Configuration
  - 3.0 in. cladding segments, defueled, refilled with Zr pellets, welded ends
  - specimens pressurized with argon gas up to 6000 psi (330 MPa)
  - Pressure regulated to ±10 psi
  - five specimens loaded in furnaces for concurrent creep testing
- Measurements
  - temperature and pressure measured for control
  - diameter measurements at multiple axial and azimuthal locations by laser profilometry
  - length measurements for possible creep anisotropy
- Derived data
  - hoop strain from diameter measurements
  - strain rate from strain-time history

Thermal Creep Tests
Specimen Test Chamber

- **Purposes**
  - preclude oxidation
  - mitigate contamination spread in case of rupture

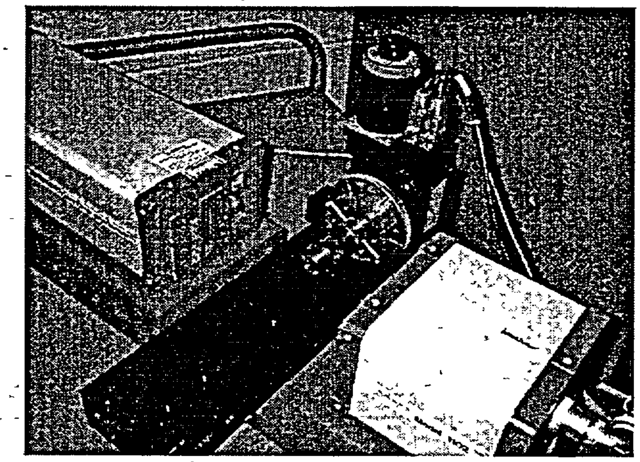
Thermal Creep Tests
Furnaces

- **One sample each in the 2 small furnaces**
- **Three samples in the large furnace**

Thermal Creep Tests
Laser Profilometry

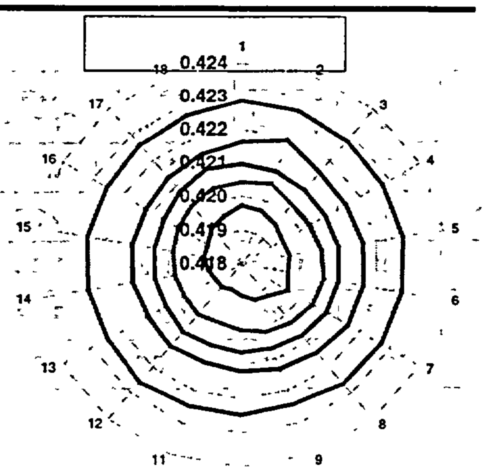
Diametral measurement intervals:
- **9° azimuthal**
- **0.3 in. axial**

Length is measured by profiling the bottom end



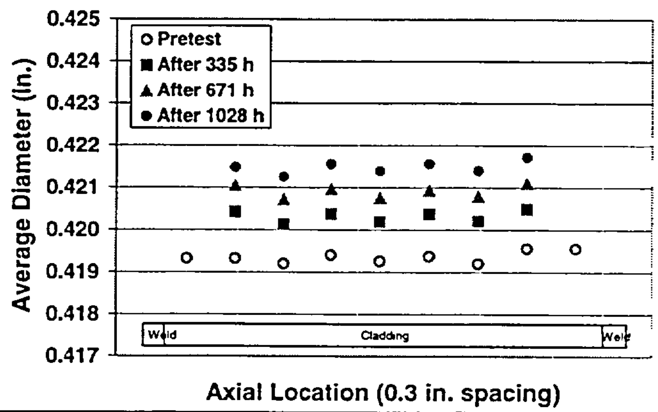
Laser Profilometry
- Data Reduction

- **Cross-sectional profile of a sample after**
  - **0 h,**
  - **335 h,**
  - **671 h,**
  - **1028 h, and**
  - **1820 h,**



Laser Profilometry
- Data Reduction

- Middle 5 axial readings are used to produce the specimen's average diameter



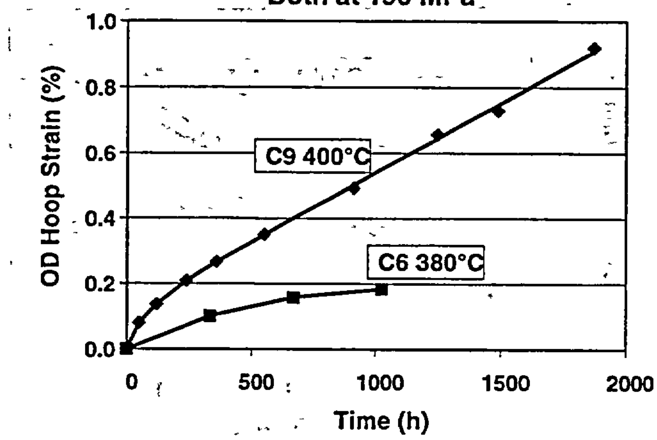
Surry Thermal Creep Tests
- Summary Results

Test No.	Temp. (°C)	Stress (MPa)	Duration (hrs)	Avg. Strain	Failure	Strain Rate (%/hr)
1	380	220	2180	1.10	No	4.5×10^{-4}
2	380	190	2348	0.35	No	8.8×10^{-5}
3	400	190	1873	1.03	No	4.9×10^{-4}
4	400	250	693	5.83	No	$>4.9 \times 10^{-3}$
5	360	220	3305	0.22	No	4.2×10^{-5}

Summary Test Results

Temperature Dependence

Both at 190 MPa



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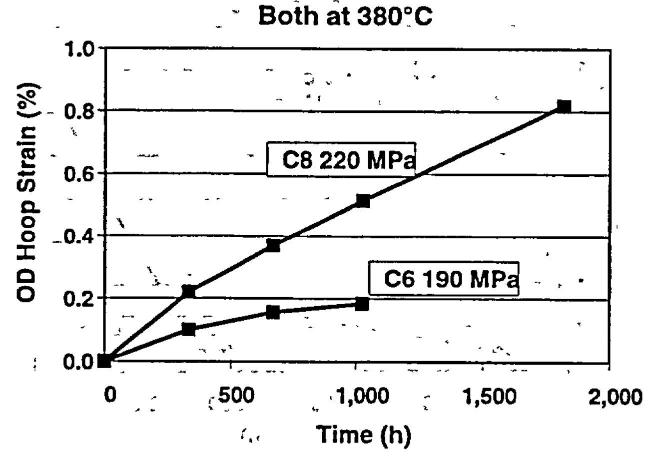
Summary Test Results

Stress Dependence

Both at 380°C



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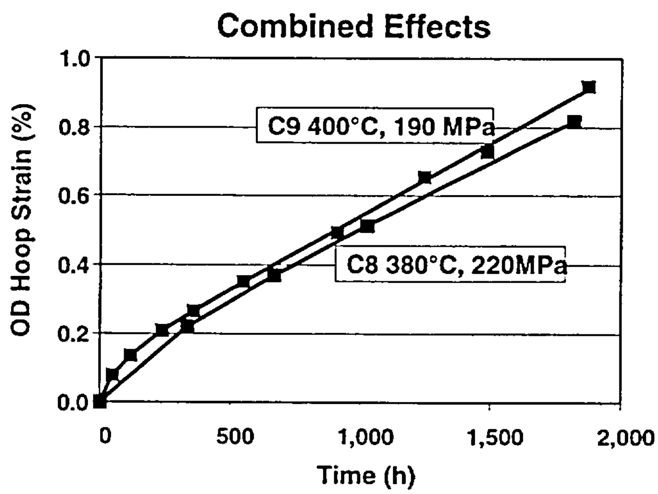
Summary Test Results



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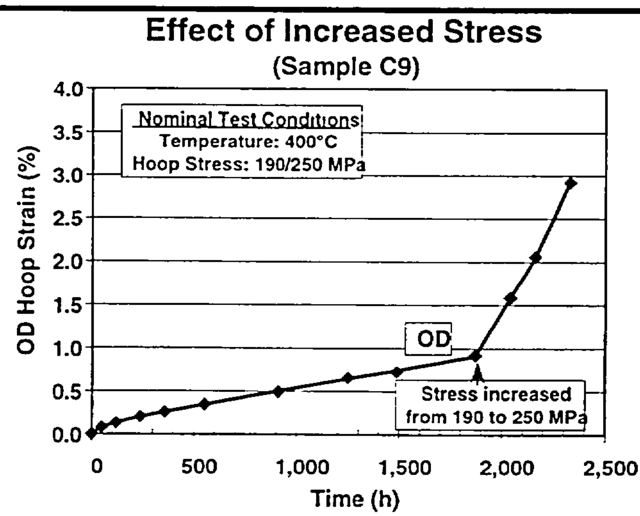
Summary Test Results



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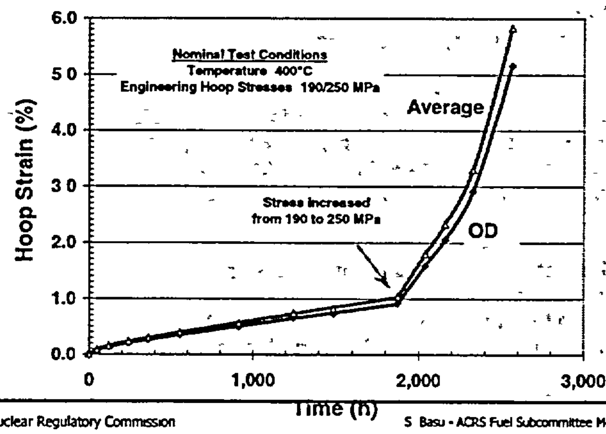
Surry Thermal Creep Results (C9)

- 400°C, 190/250 MPa engineering hoop stress, 2566 h
- 5.8% average hoop strain, no rupture



Conclusions of Surry Creep Testing Program

- Significant residual creep strain demonstrated for Surry cladding after 15-y dry-cask storage
- Creep data show strong temperature and stress dependency in the regime tested
- Two additional tests at 400°C and 160 MPa and 220 MPa, respectively, planned to expand the database
- Data on possible hydride reorientation and post-creep ductility to be generated
- Lower temperature tests for permanent repository applications may also be carried out in future

High Burnup Spent Fuel Testing for Dry Cask Storage

- **Program Program Scope**
  - fuel and cladding characterization
  - isotopic analysis
  - annealing tests
  - thermal creep tests
  - mechanical properties tests
- **Cladding Material**
  - H.B. Robinson PWR rods: 2 rods (2.9% enrichment, 67 GWd/MTU); one rod (1.9% enrichment, 10% Gd_2O_3, 47 GWd/MTU)
  - OD oxide thickness ~ 60 μm to 110 μm
  - hydrogen content ~ 580 wppm to 750 wppm
- **Program Status**
  - characterization and isotopic analysis in progress
  - annealing tests completed
  - creep test matrix developed; lead test started
  - mechanical properties testing planned

Robinson Cladding Annealing Test Results

- Using microhardness as the figure-of-merit, determined percent recovery of radiation damage in cladding
- Preliminary findings – annealing can produce significant recovery

Robinson Zry-4	H wppm	Annealing		Vickers DPH	% Recovery
		Temp.°C	Time, h		
Nonirrad.	<10	---	---	203	100
As-irrad.	≈600	---	---	252	0
As-irrad. & Annealed	≈600	420	20 72	226 215	54 75
As-irrad. & Annealed	≈600	450	2 10	224 217	58 71
As-irrad. & Annealed	≈600	500	2 48	218 206	69 94

High Burnup Thermal Creep

- **Testing Strategy**
  - Conduct two lead tests duplicating Surry test conditions to determine effects of Robinson's higher hydrogen content and fast fluence
    - One of the lead tests has been started
  - Establish test matrix based on lead test results
    - Simple and flexible
    - Emphasizing 400°C
  - Duplicate Surry creep testing techniques
    - 5 additional systems being built

Preliminary HBR Creep Matrix
(07/12/02 Version)

H-content wppm	Temp. °C	Stress MPa	Time h	Predicted Strain, %
650±50	400	220	TBD	TBC
650±50	400	190	TBD	TBC
650±50	400	160	TBD	TBC
650±50	420	160	TBD	TBC
650±50	380	220	TBD	TBC
650±50	380	190	TBD	TBC
650±50	380	160	TBD	TBC
650±50	360	220	TBD	TBC
650±50	360	190	TBD	TBC